US010098585B2

(12) **United States Patent**
Scott et al.

(10) **Patent No.: US 10,098,585 B2**
(45) **Date of Patent: Oct. 16, 2018**

(54) **NEUROMONITORING SYSTEMS AND METHODS**

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(73) Assignee: **Cadwell Laboratories, Inc.**, Kennewick, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 11 days.

(21) Appl. No.: **14/206,945**

(22) Filed: **Mar. 12, 2014**

(65) **Prior Publication Data**

US 2014/0275926 A1 Sep. 18, 2014

Related U.S. Application Data

(60) Provisional application No. 61/792,339, filed on Mar. 15, 2013.

(51) **Int. Cl.**

A61B 5/00 (2006.01)
A61B 5/04 (2006.01)
A61N 1/36 (2006.01)

(52) **U.S. Cl.**

CPC ***A61B 5/4893*** (2013.01); ***A61B 5/04001*** (2013.01); ***A61B 5/4041*** (2013.01); *A61N 1/36017* (2013.01)

(58) **Field of Classification Search**

CPC . A61B 5/04001; A61B 5/4041; A61B 5/4047; A61B 5/4052; A61B 5/0488; A61B 5/4893

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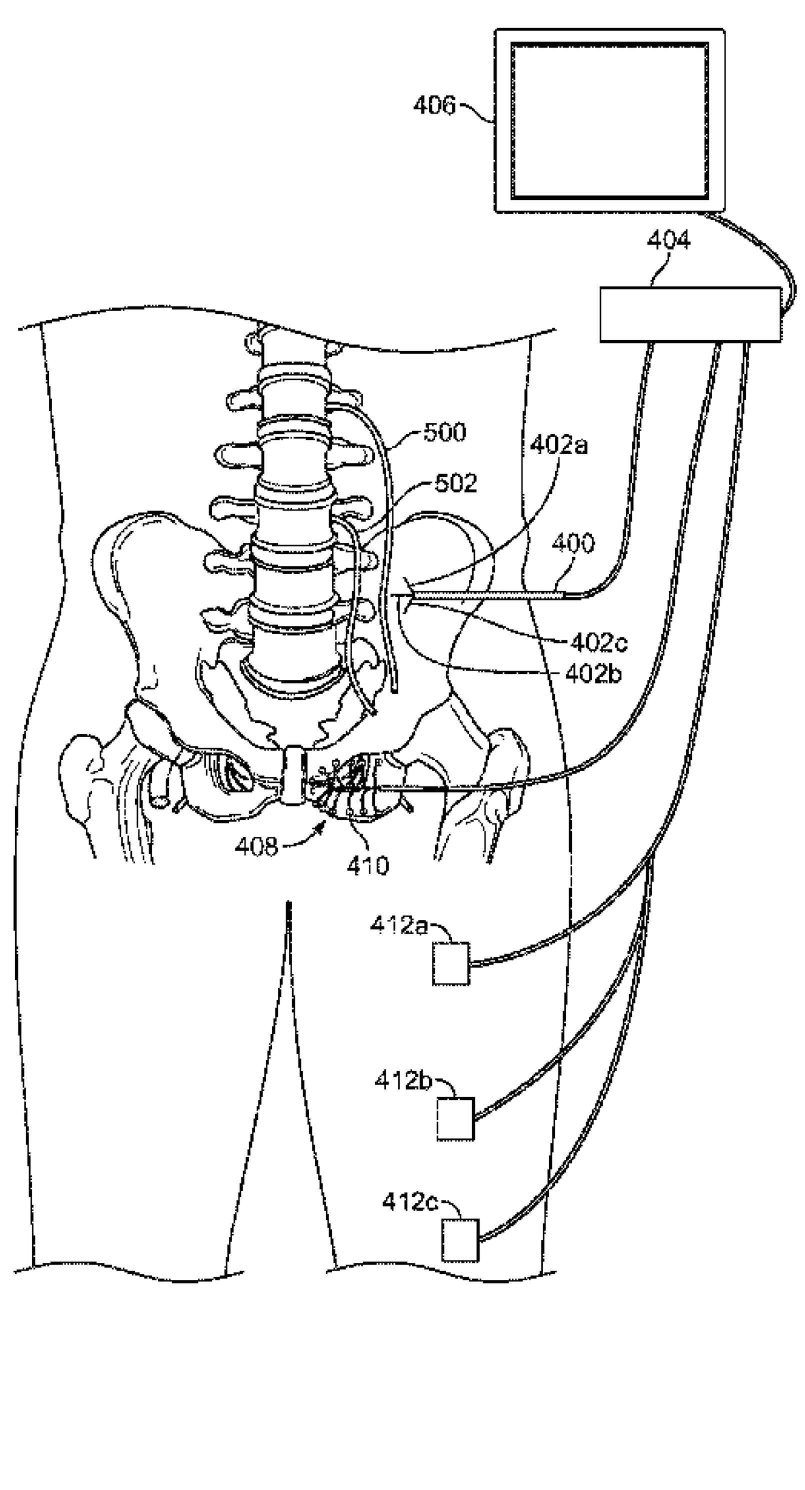
Primary Examiner — Adam J Eiseman
(74) *Attorney, Agent, or Firm* — Novel IP

(57) **ABSTRACT**

Systems, devices and methods are provided for neuromonitoring, particularly neuromonitoring to reduce the risks of contacting or damaging nerves or causing patient discomfort during and after surgical procedures, including spinal surgeries. The neuromonitoring procedures include monitoring for the presence of or damage to sensory nerves, and optionally includes additional monitoring for motor nerves. In some systems, including systems that monitor for both sensory and motor nerves, components of the monitoring systems (e.g., stimulating electrodes and response sensors), may be combined with one or more surgical instruments. The systems, devices, and methods provide for pre-surgical assessment of neural anatomy and surgical planning, intra-operative monitoring of nerve condition, and post-operative assessment of nerve position and health.

14 Claims, 12 Drawing Sheets



(58) **Field of Classification Search**
USPC 600/546, 547, 595
See application file for complete search history.

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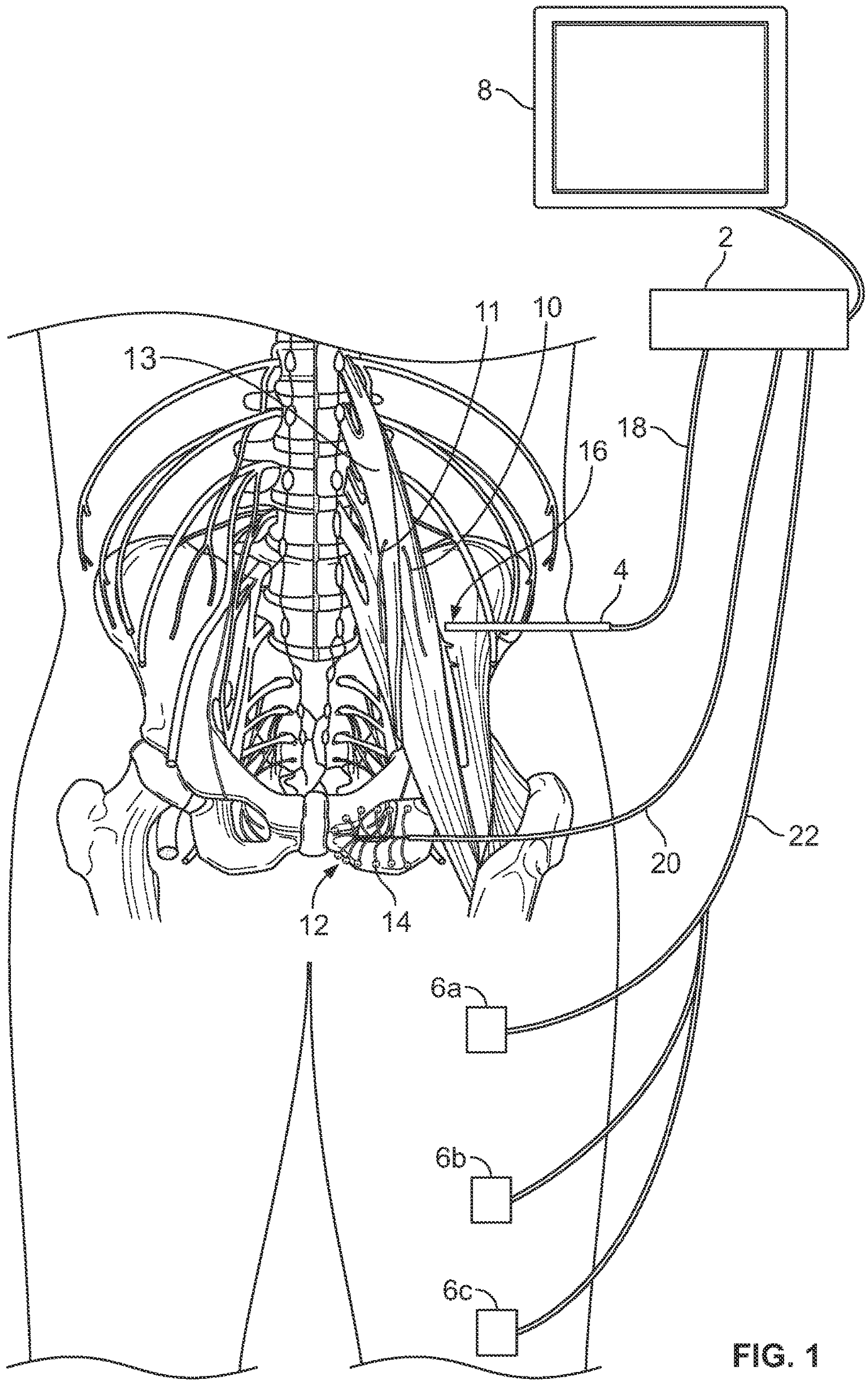
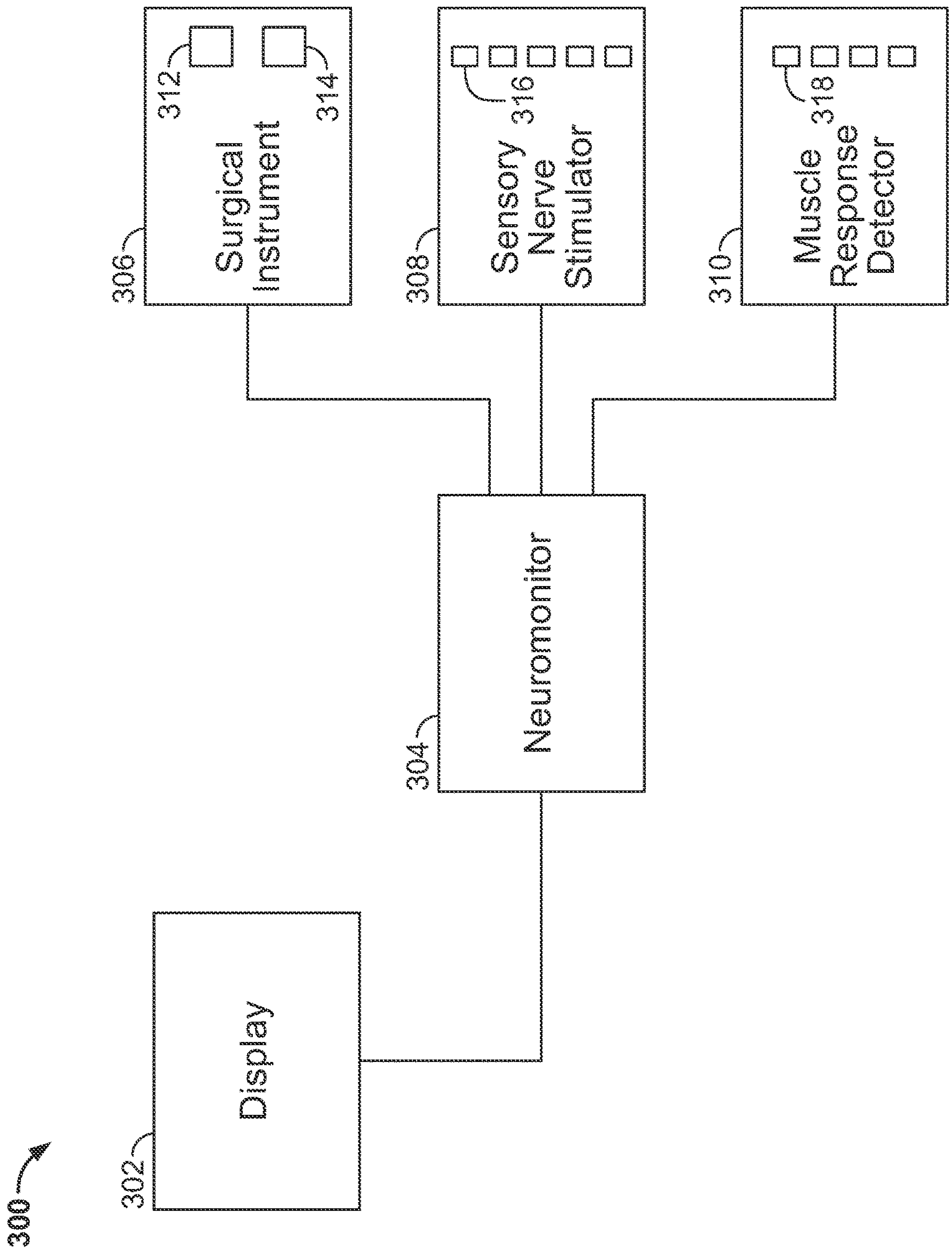


FIG. 1



300
302
Display
304
Neuromonitor
306
Surgical Instrument
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314
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Sensory Nerve Stimulator
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Muscle Response Detector
318

FIG. 2

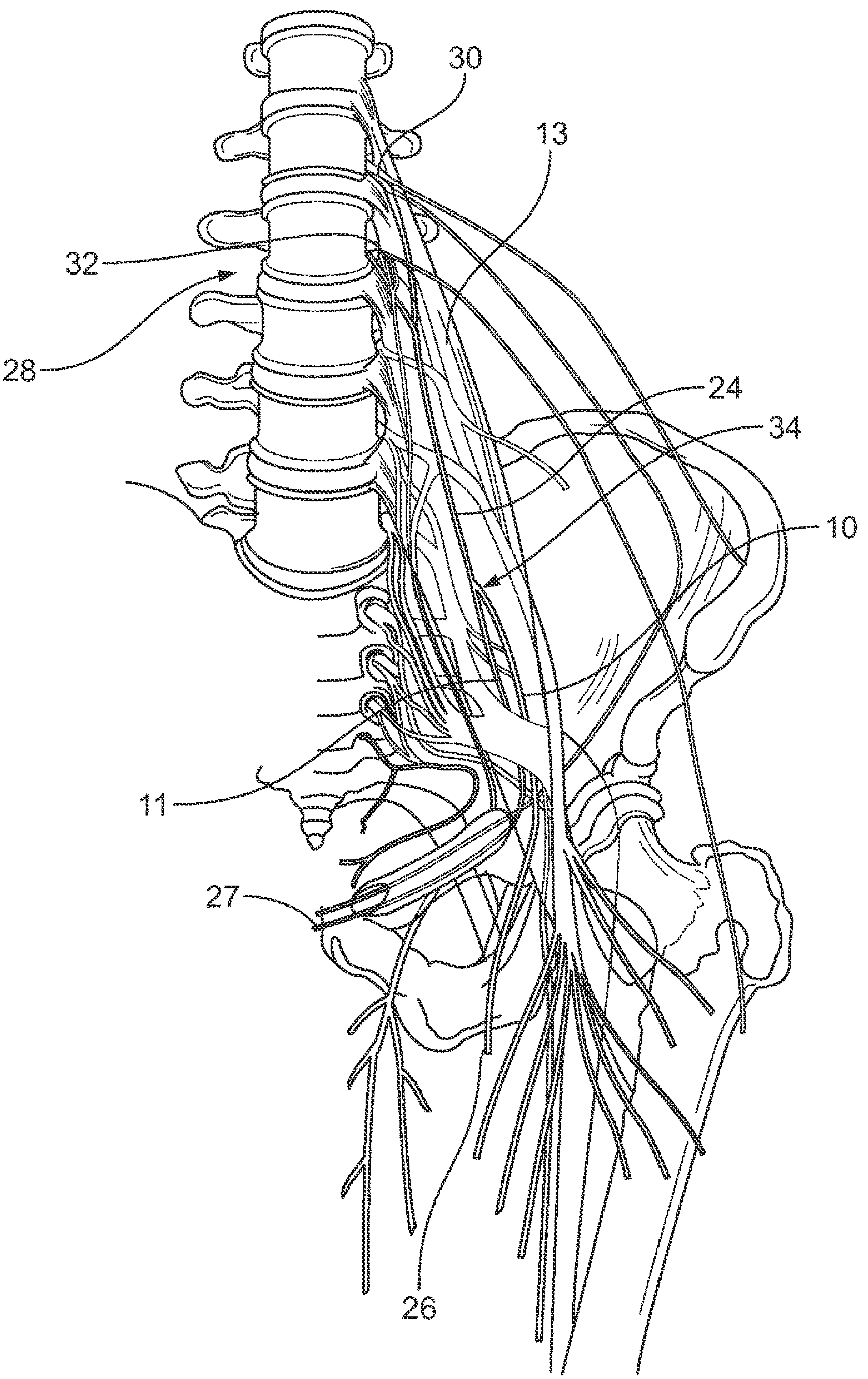


FIG. 3

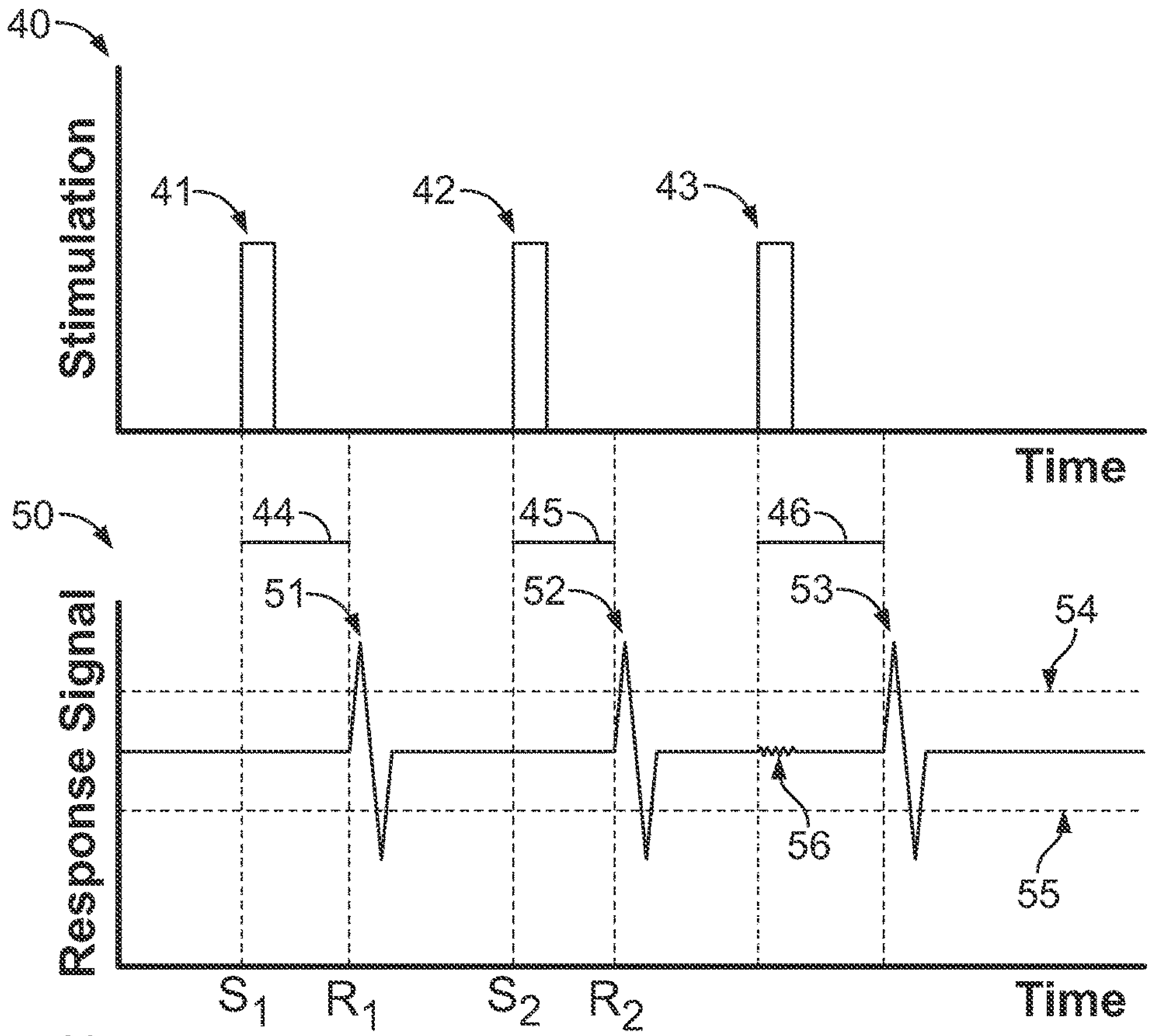
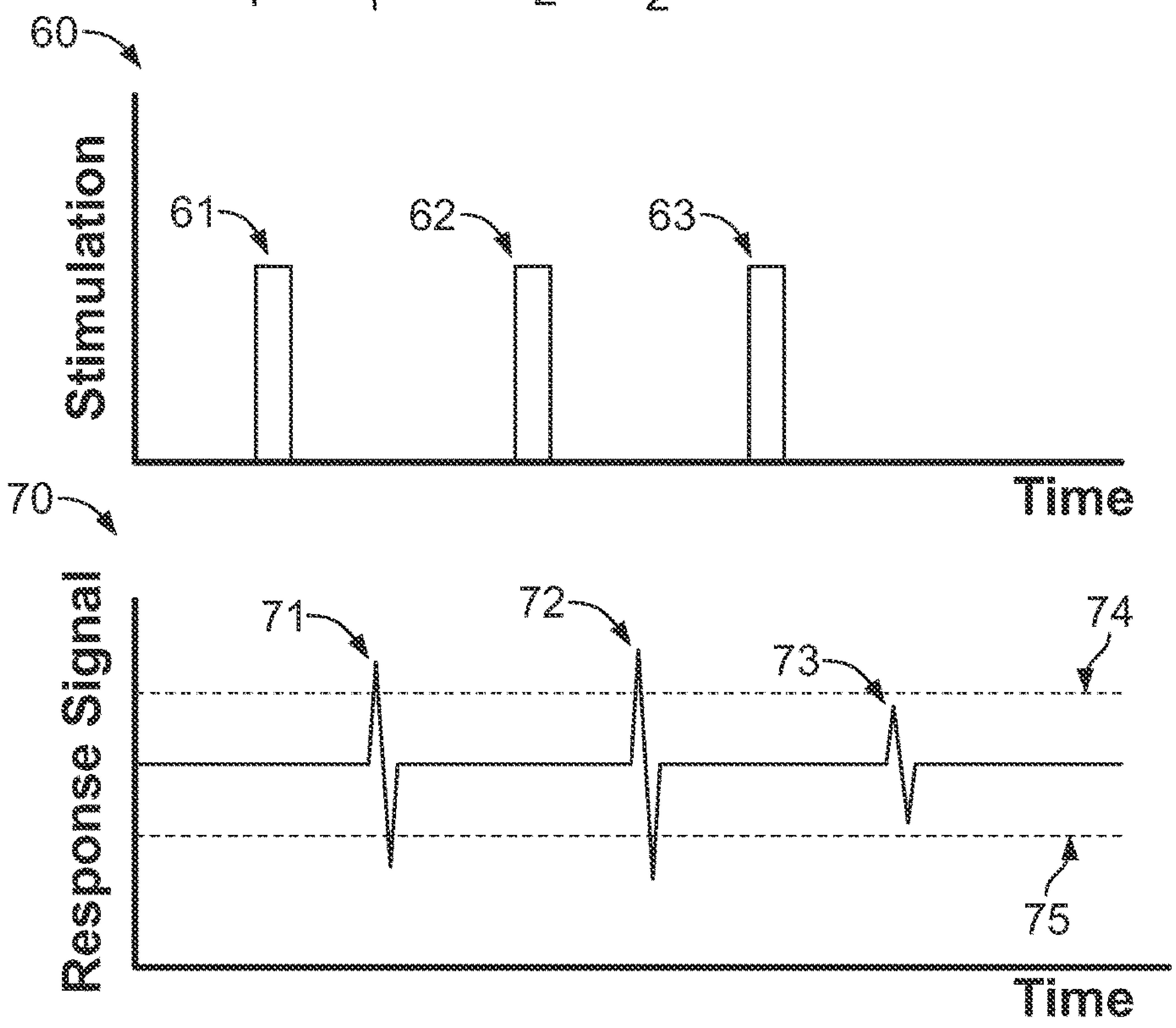

40
Stimulation
41
42
43
Time
50
44
45
46
Response Signal
51
52
53
54
56
55
S1
R1
S2
R2
Time

FIG. 4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Stimulation
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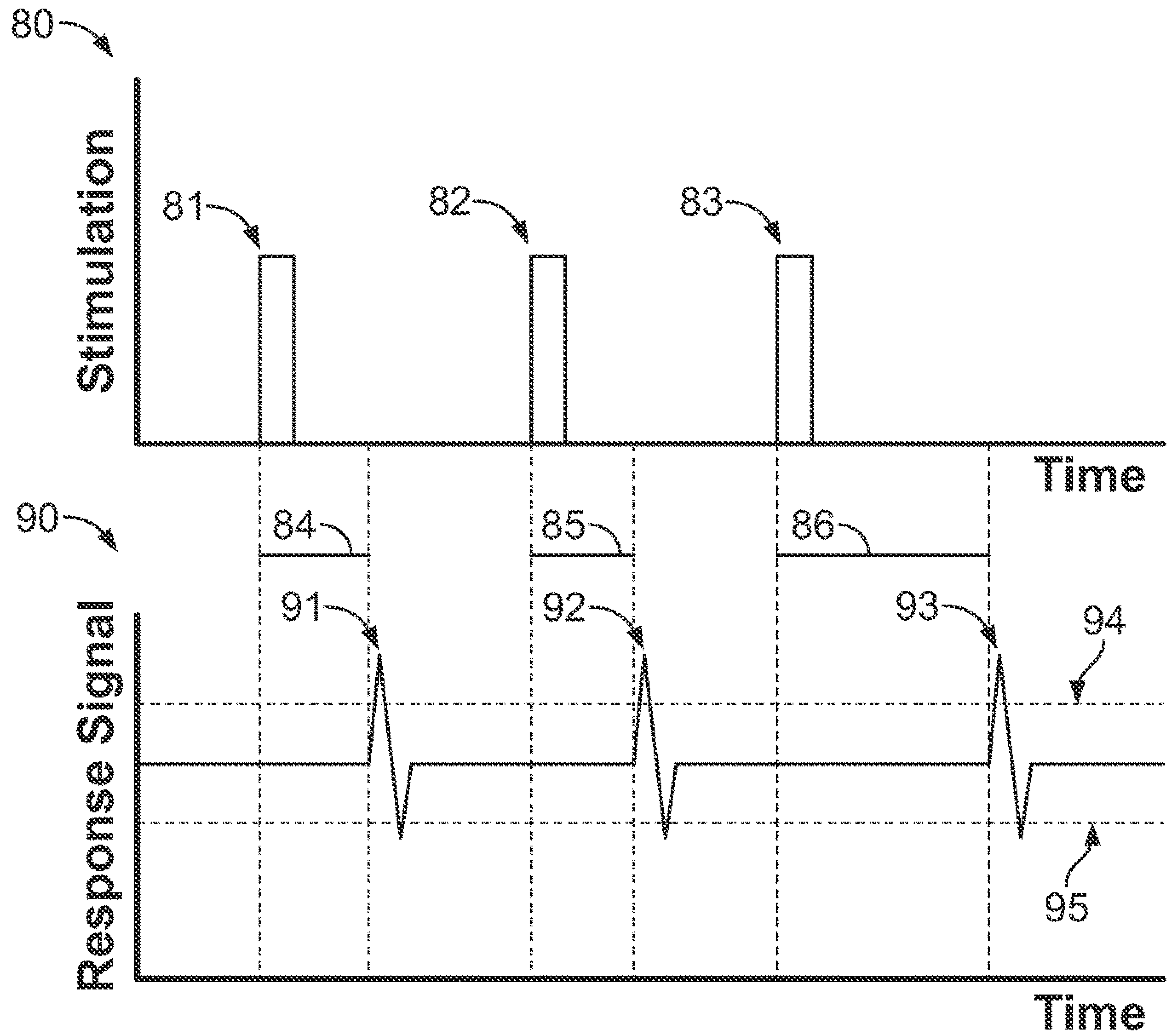
62
63
Time
70
Response Signal
71
72
73
74
75
Time

FIG. 5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Stimulation
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Time
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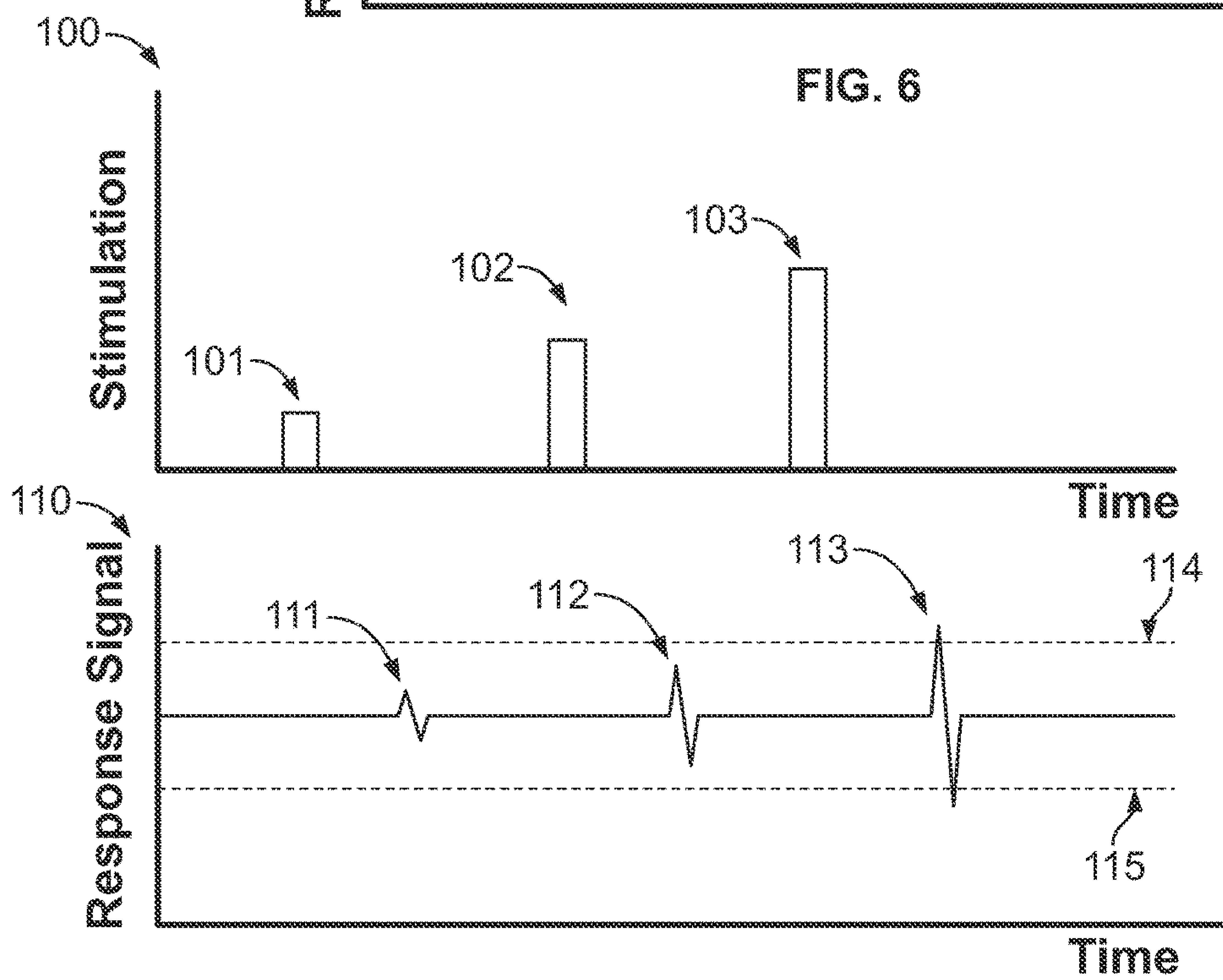
84
85
86
91
92
93
94
Response Signal
95
Time

FIG. 6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Stimulation
101
102
103
Time
110
Response Signal
111
112
113
114
115
Time

FIG. 7

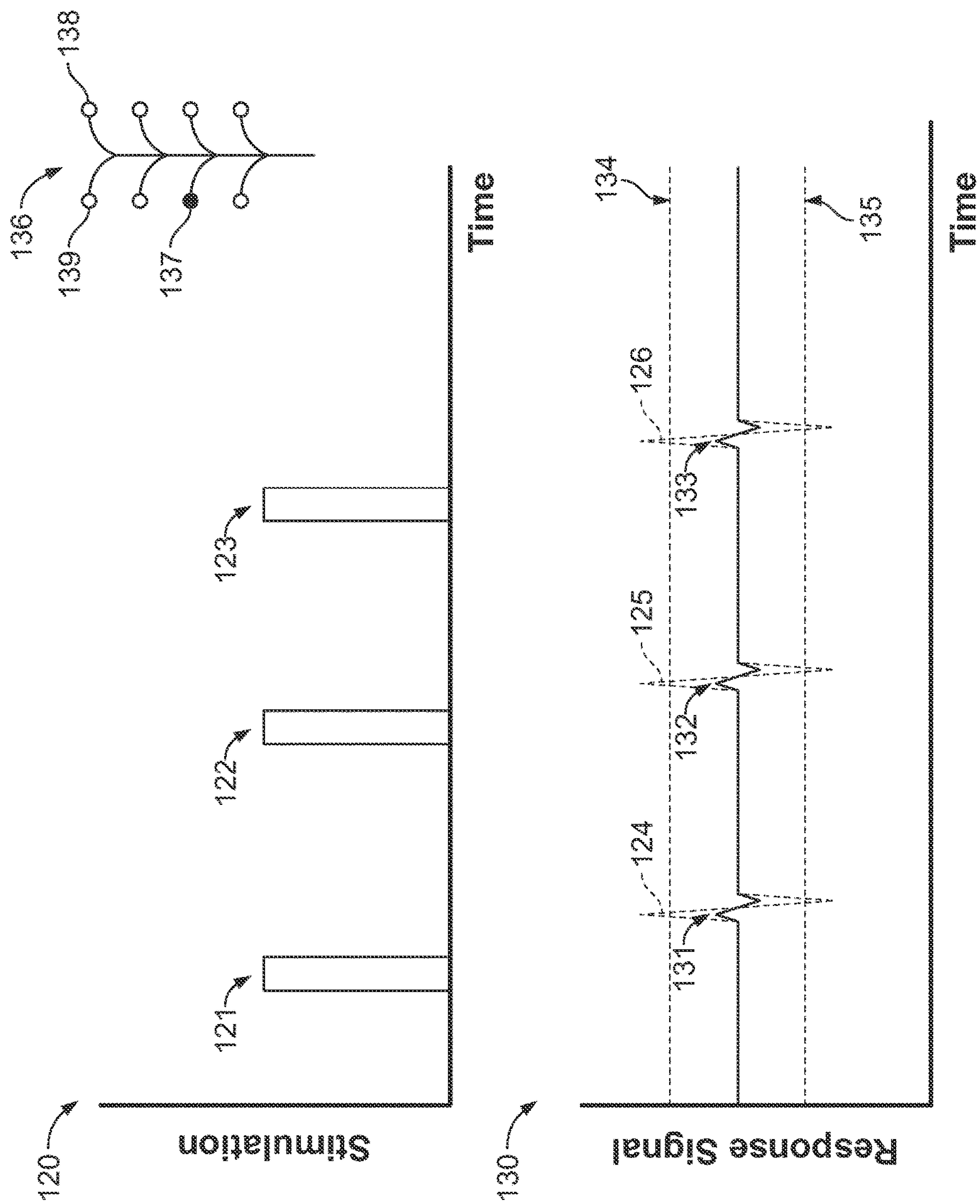
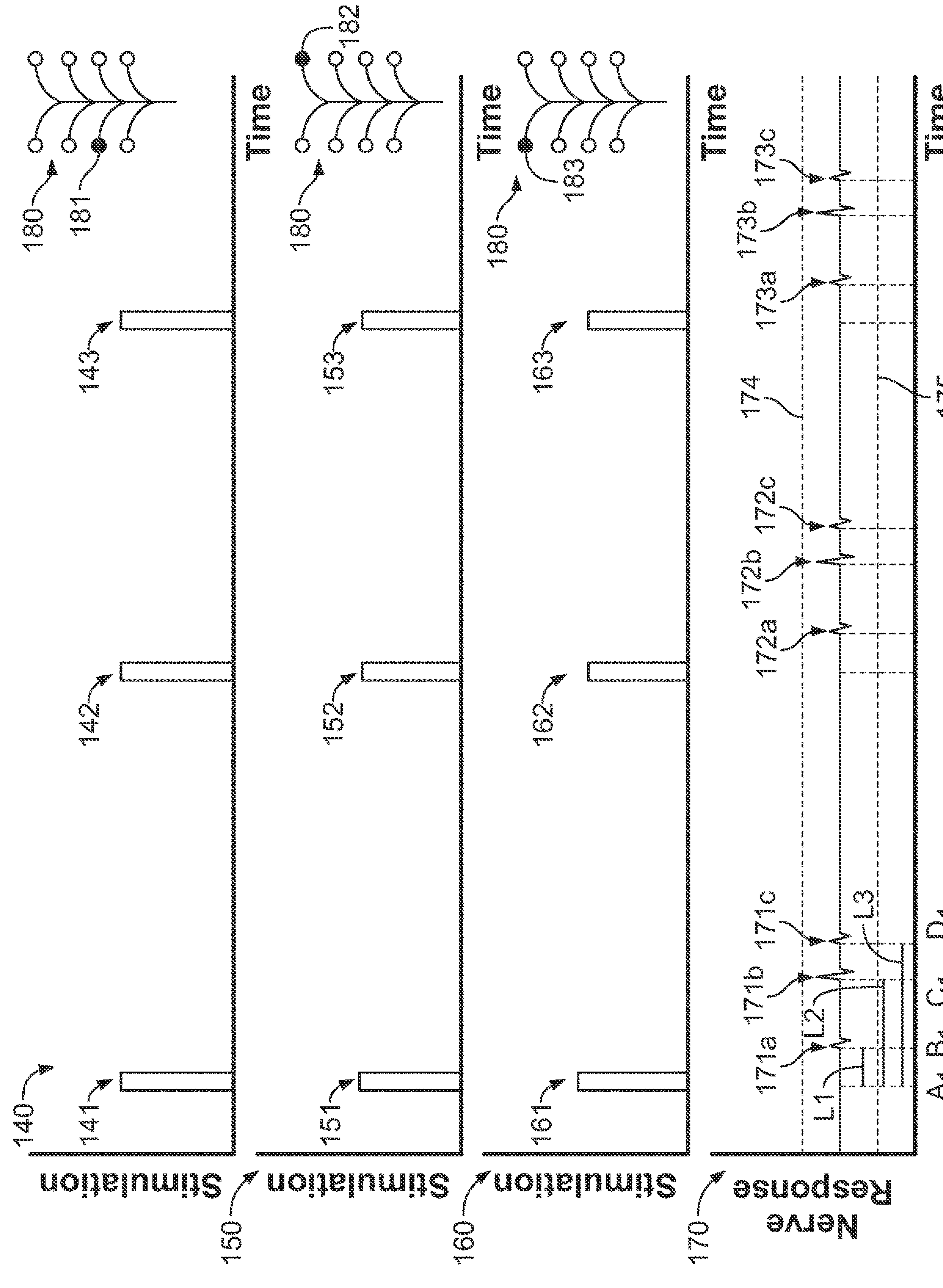

136
138
139
137
120
Stimulation
121
122
123
Time
130
Response Signal
131
124
132
125
133
126
134
135
Time

FIG. 8



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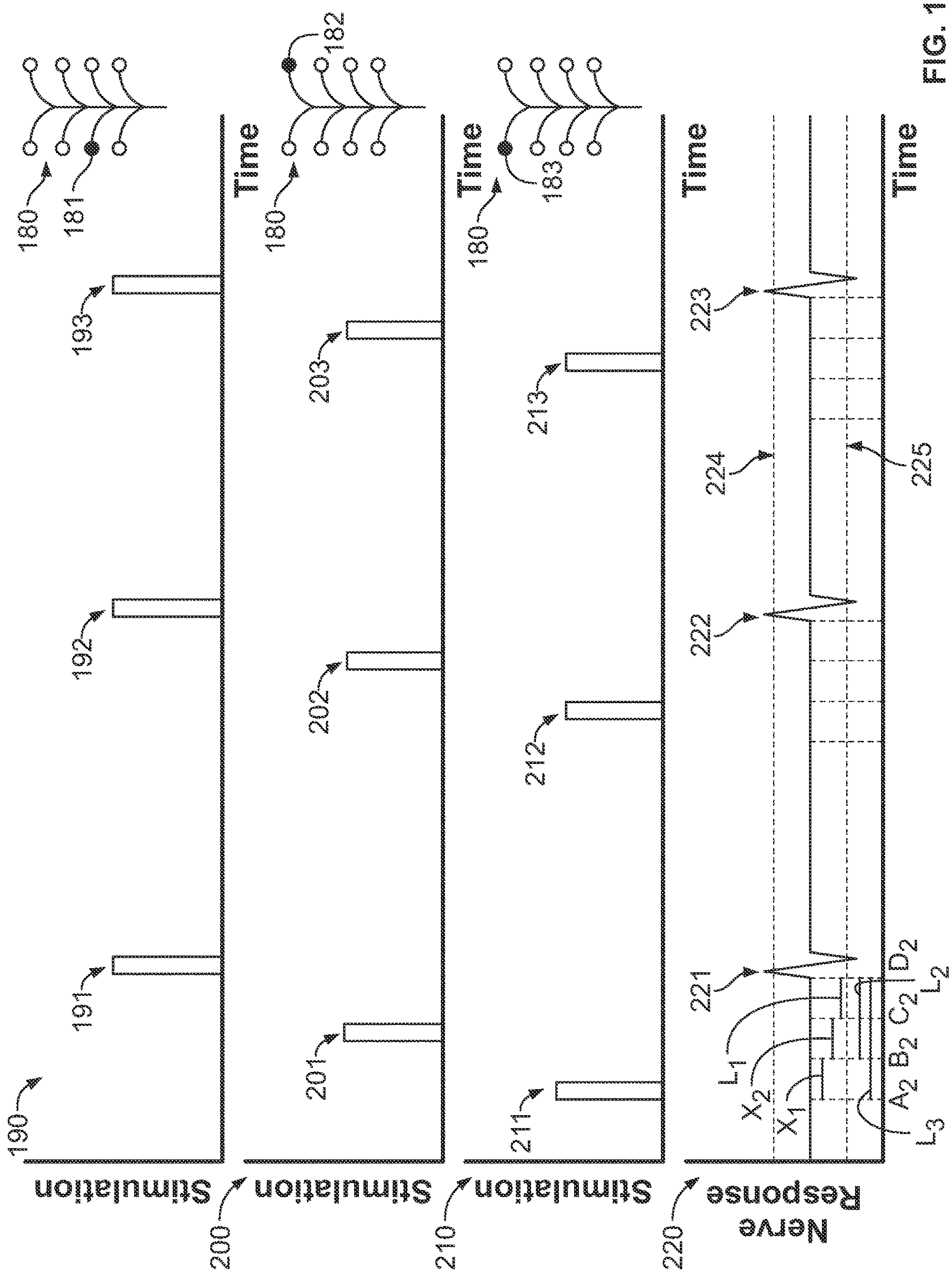
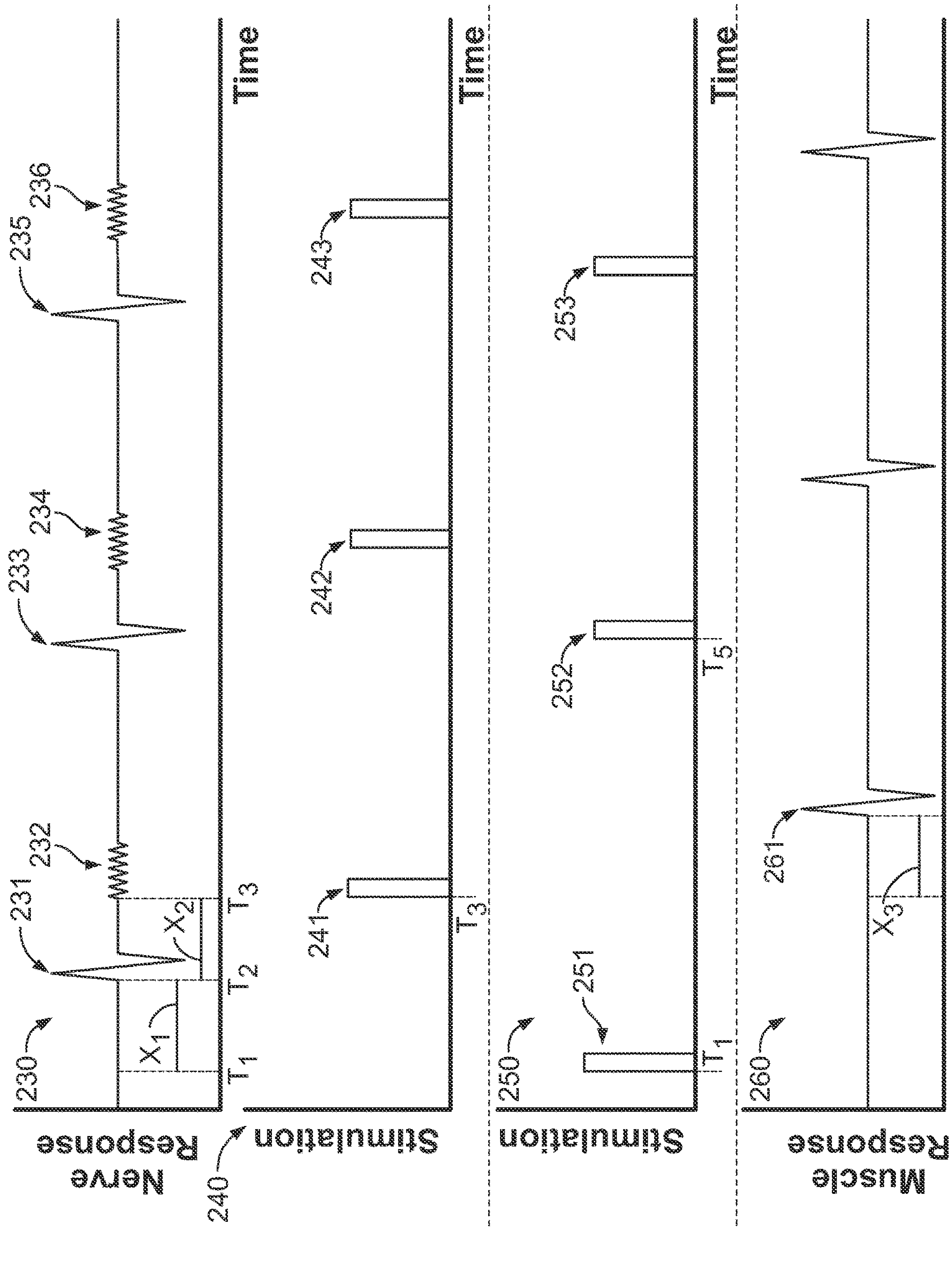
153
160
161
162
163
170
171a
171b
171c
172a
172b
172c
173a
173b
173c
174
175
L1
L2
L3
A1 B1 C1 D1
Stimulation
Stimulation
Stimulation
Nerve Response
Time
Time
Time
Time

FIG. 9



190
Stimulation
Time
191
192
193
180
181
200
Stimulation
Time
201
202
203
180
182
210
Stimulation
Time
211
212
213
180
183
220
Nerve Response
Time
221
222
223
224
225
L_1
L_2
L_3
X_1
X_2
A_2
B_2
C_2
D_2

FIG. 10



Nerve Response
Stimulation
Stimulation
Muscle Response
Time
Time
Time
Time
230
231
232
233
234
235
236
240
241
242
243
250
251
252
253
260
261
X_1
X_2
X_3
T_1
T_2
T_3
T_3
T_1
T_5
T_3
T_4

FIG. 11

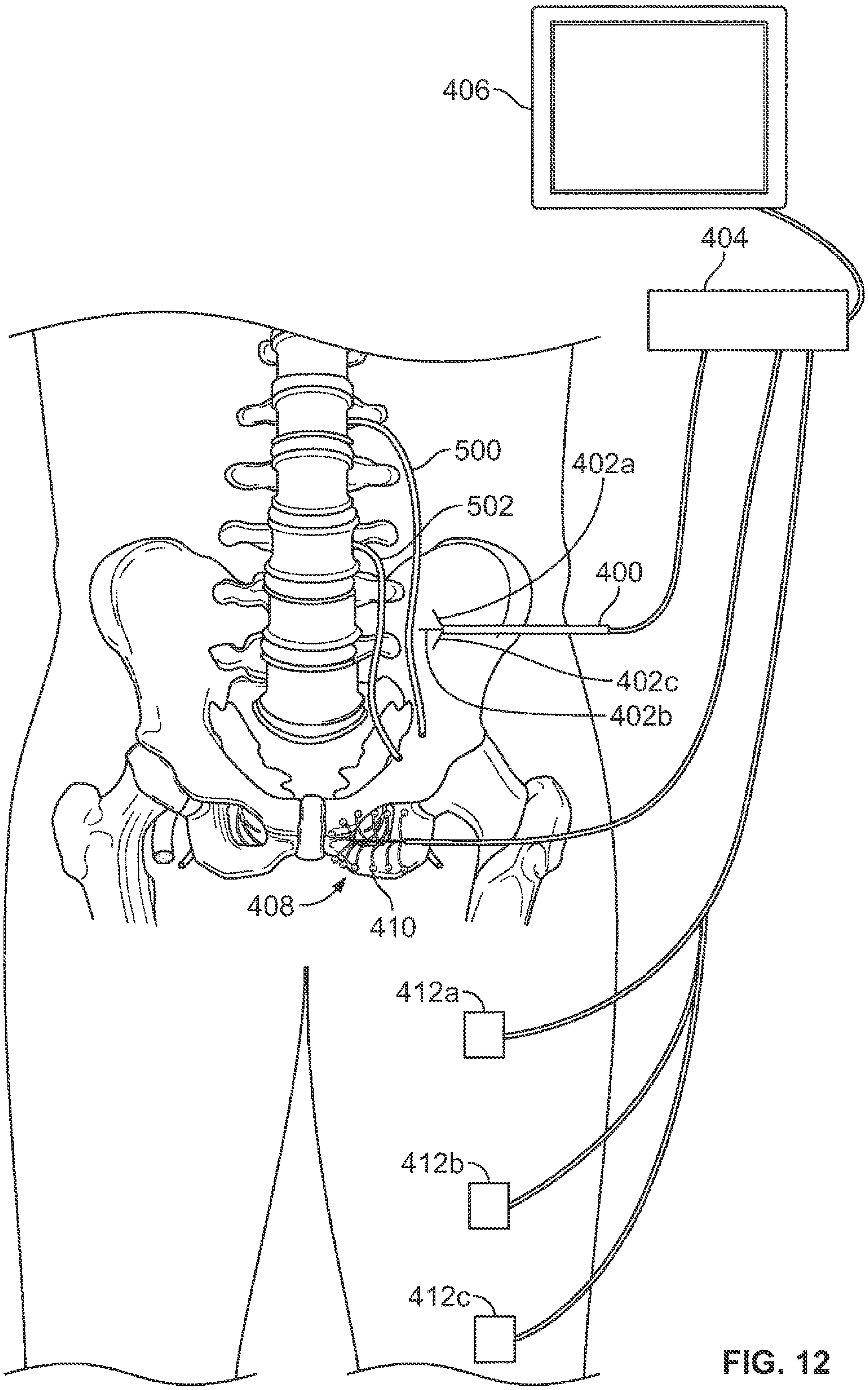


FIG. 12

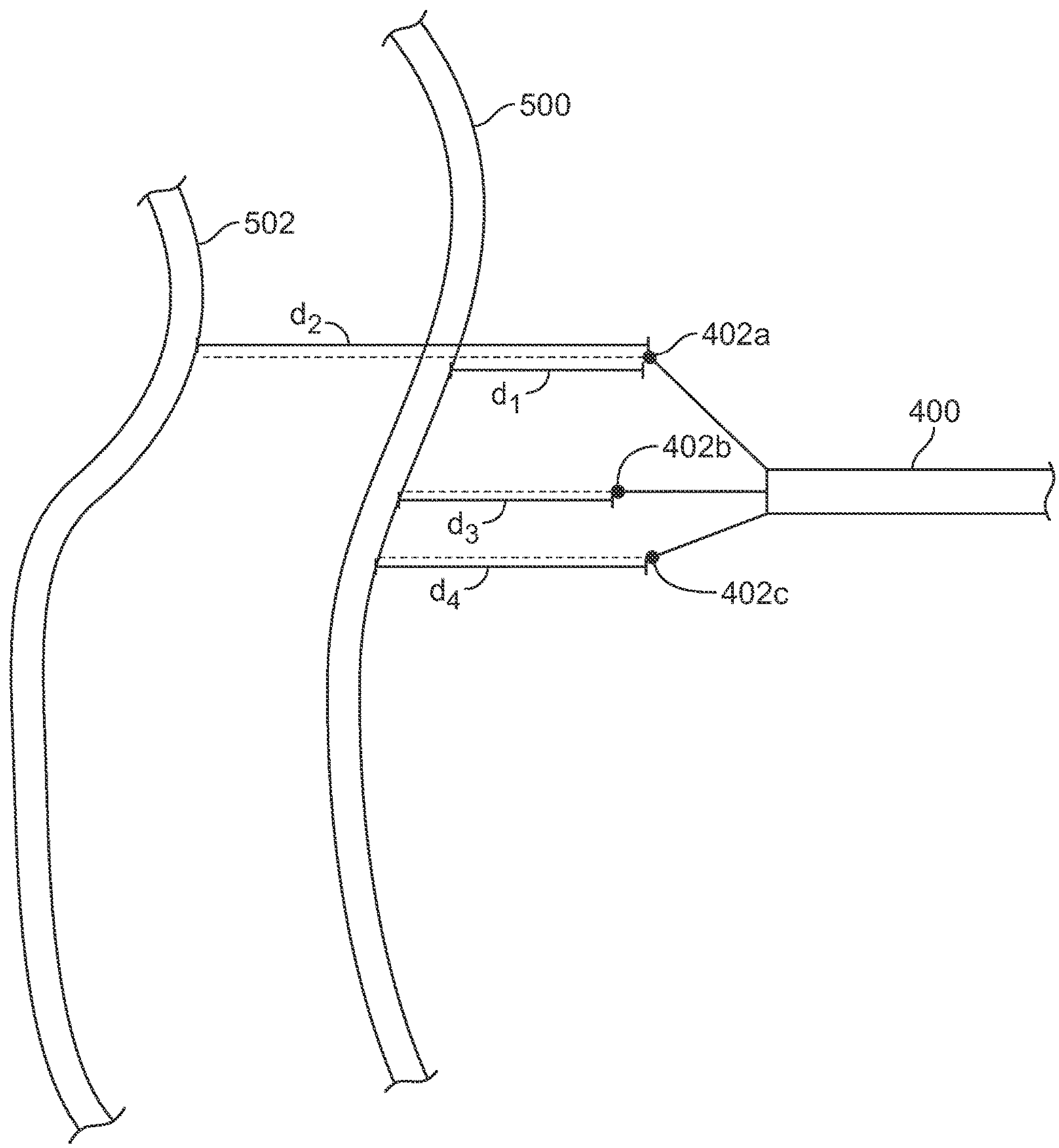
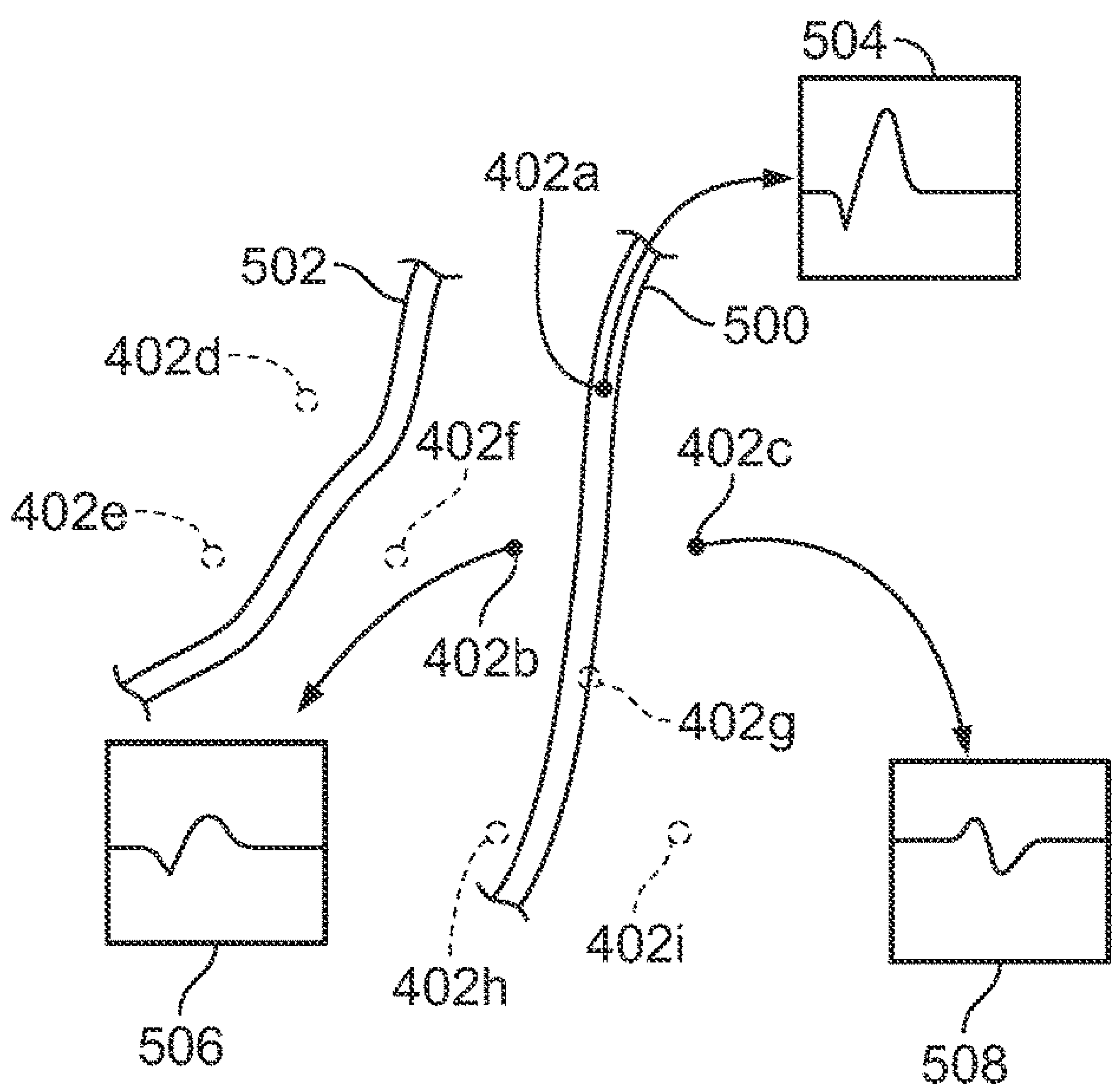


FIG. 13



504
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402d
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402c
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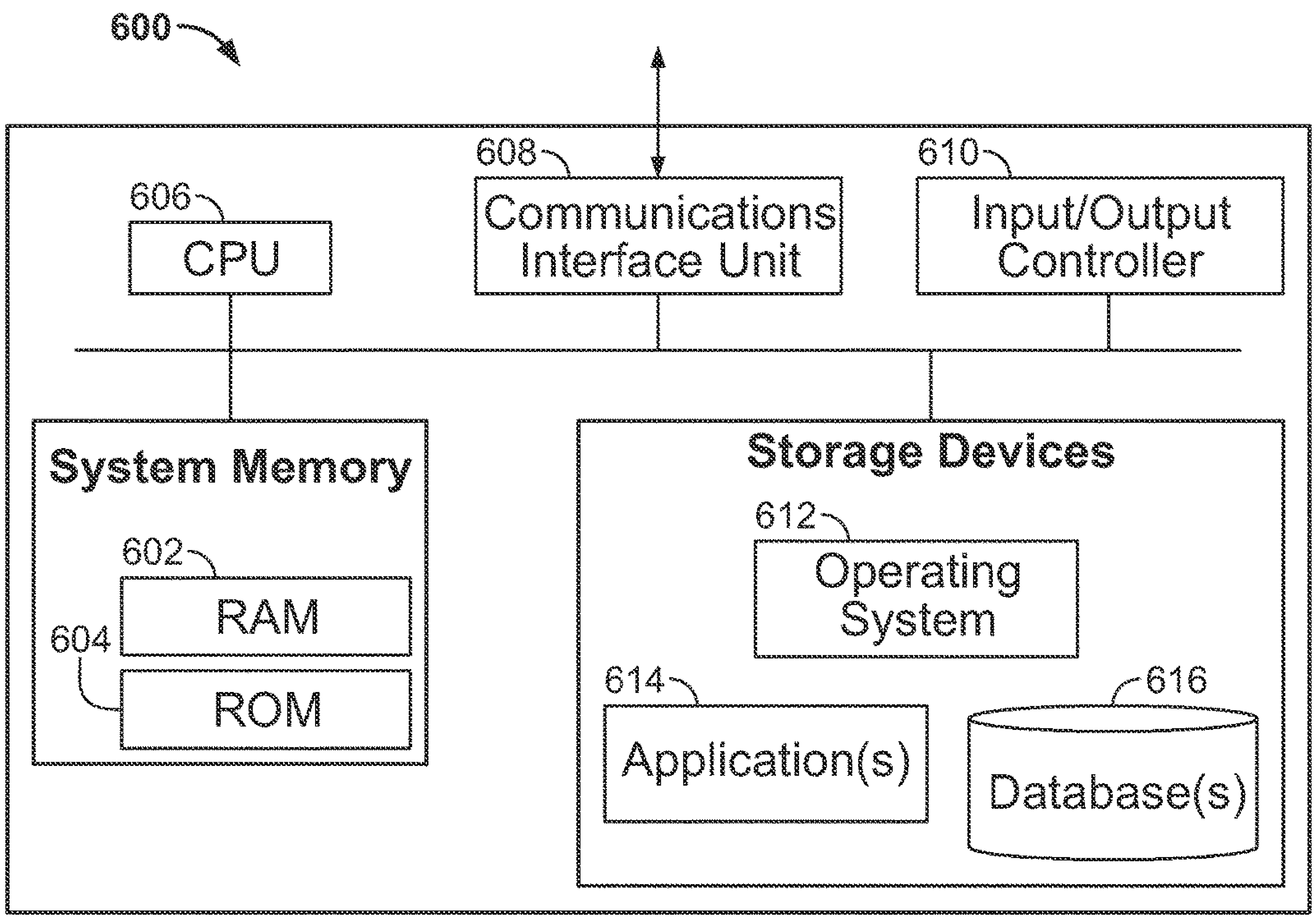
402b
402g
402h
402i
506
508

FIG. 14



600
608
610
606
Communications Interface Unit
Input/Output Controller
CPU
System Memory
Storage Devices
602
RAM
604
ROM
612
Operating System
614
616
Application(s)
Database(s)

FIG. 15

NEUROMONITORING SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 61/792,339, filed Mar. 15, 2013, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

The risk of injury to a nerve is a concern when performing surgical procedures, including minimally invasive procedures, within close proximity to the spine or spinal nerves. Surgeons increasingly rely on neuromonitoring techniques to monitor the nerves during such surgeries in order to avoid inadvertently injuring or contacting a nerve. Prior devices have been developed to help surgeons avoid contacting and damaging nerves during these procedures, but improvements are needed for enhancing the monitoring capabilities of those devices.

In some spinal surgeries, a patient's spine is accessed and viewed by anterior, posterior, or lateral approaches in which instruments for the surgery are advanced to the spine. When approaching the patient's spine, care must be taken to avoid nerves, in particular to avoid spinal nerves that exit the spinal cord at nerve roots extending through the spinal vertebrae. These spinal nerves include motor nerves, which control muscle activity throughout the body, and sensory nerves, which receive sensory input and relay the sensory input to the spinal cord and brain. During spinal surgeries, both motor and sensory nerves may be present in the muscle and tissue through which instruments are advanced to access the spine. Some techniques monitor muscle EMG responses during surgery to identify when a surgical tool is too close to a nerve. But those techniques do not address potential damage to sensory nerves, such as the genitofemoral nerve, that may also be near the surgical site. If damage to the nerves is not avoided, a patient may suffer post-surgery partial paralysis or pain resulting from the nerve damage.

SUMMARY

Disclosed herein are systems, devices and methods for neuromonitoring, particularly neuromonitoring to reduce the risks of contacting or damaging nerves or causing patient discomfort during and after surgical procedures, including spinal surgeries. The neuromonitoring procedures include monitoring for the presence of or damage to sensory nerves, and optionally includes additional monitoring for motor nerves. In some systems, including systems that monitor for both sensory and motor nerves, components of the monitoring systems (e.g., stimulating electrodes and response sensors), may be combined with one or more surgical instruments.

During a spinal surgical procedure, surgical instruments approaching the spine may encounter both sensory and motor nerves that exit the lateral sides of the spine. The motor nerve roots exiting the spine run to peripheral muscles and innervate those muscles to control both voluntary and involuntary contraction of the muscles. Nerve signals running through these motor nerves originate in the brain, pass through the spinal cord, and run through a particular peripheral nerve to the innervated muscle being controlled. Sensory nerves, on the other hand, relay sensory information from peripheral sensors, such as skin mechanoreceptors, to the spinal cord and the brain. Mixed nerves have both motor and sensory functions, with some fibers of the nerve innervating muscles and other fibers of the nerve relaying sensory information to the brain. The combination of the motor, sensory, and mixed nerves creates a two-way pathway of communication between the central nervous system (brain and spinal cord) and peripheral tissues. Signals in motor nerves or fibers travel in one direction from the brain to the periphery, while signals in sensory nerves or fibers travel in the opposite direction from the periphery to the brain. In monitoring for these nerves during any surgical procedure, the systems, devices, and methods disclosed herein may make use of this two-way pathway to stimulate and sense responses from both motor and sensory nerves or fibers, so as to detect sensitive nerve tissues and help guide surgical tools.

Motor nerves can be monitored by stimulating the nerves near or at the nerve root and monitoring peripheral muscles innervated by the nerves for muscle responses caused by the delivered stimulation. The stimulation may be delivered by applying any suitable stimulus signals, including voltage and/or current pulses of varying amplitude, pulse width, and/or frequency. With surgical instruments approaching the spine, stimulation may be delivered during the approach from a distal end of a surgical instrument, and peripheral muscles, for example muscles in the legs, can be monitored using EMG sensors to detect triggered responses from stimulated nerves. Stimulation may also be provided after establishing the operative corridor (e.g., after a surgical tool has advanced to the operative site). For vertebral pedicle integrity assessments, stimulation may be delivered before, during, and/or after the formation of a hole drilled to receive a pedicle screw, as well as before, during, and/or after the pedicle screw is introduced into the hole. When monitoring for changes in nerve pathology, stimulation may be performed before, during, and/or after contact with the nerve (e.g., before, during, and/or after retraction of the nerve root). The response of the nerve to the stimulation can be measured in any suitable fashion, such as by monitoring the evoked muscle action potential. For example, a sensed EMG signal of muscles associated with the nerve may be measured to indicate that a surgical instrument is approaching or impinging on the nerve and is used to warn a surgeon during the approach or at any time during or after the surgical procedure. Such neuromonitoring systems and methods may be, for example, similar to the systems and methods described in U.S. Provisional Application Nos. 61/721,482, 61/796,207, and 61/730,202, which are hereby fully incorporated by reference herein.

In contrast to motor nerves, sensory nerves do not innervate muscles and do not cause muscle reactions when roots of the nerves exiting the spine are stimulated, yet they are important to normal nervous system functions and should be avoided during surgery. Electrical stimulation delivered from a surgical instrument near the spine may not produce any detectable signal from the sensory nerves because the signals in those nerves are not amplified by muscle activity like signals in motor nerves. Thus, in order to detect the sensory nerves, in preferred embodiments stimulation causing a response from the nerves is delivered at the innervated peripheral tissue and detected near the nerve root exiting from the spine, as the nerve signal travels toward the spine and the brain. As with motor nerves, the stimulation may be provided using suitable stimulation signals, including by applying voltage and/or current pulses of varying amplitude, pulse width, and/or frequency. Just as a motor nerve, or motor fibers in a mixed nerve, innervates a known muscle or muscle group, sensory nerves innervate known sensory tissues in the periphery. Thus, by delivering a stimulus to a given sensory tissue, for example a skin dermatome, the system may monitor for a detectable electrical response near the spine, and the detected response can be processed by a processor or other computer component and attributed to the particular sensory nerve that is known to innervate the stimulated tissue. The detected response is caused by an action potential that propagates through the nerve towards the brain after the sensory stimulation is delivered. To detect the signal, a response sensor is positioned near the nerve between the nerve ending in the sensory tissue and the nerve ending in the brain. For example, sensors may be positioned near a branch of the peripheral nerve, near the nerve root exiting the spine, near the spinal cord, or on a patient's head near the brain. When the response signals are monitored for a plurality of stimulations (e.g., sequential stimulations), changes in the responses, such as changes in the amplitude, frequency, or latency of the responses, can signal a problem with the monitored nerve. By utilizing this sensory nerve detecting approach, sensory nerves that are not readily detectable by motor nerve EMG monitoring techniques may be detected.

In some implementations, neuromonitoring techniques described herein are employed before a surgical procedure is performed to assess and map a patient's nerve anatomy. Delivered stimulation and responses detected from sensory nerves, and also motor nerves in some approaches, are used to determine the distances from the nerves to probes located at different positions. The distances and positions are used to locate the nearby nerves and create a map of the nerve anatomy near the spine, or near a desired surgical site. A probe can be moved to multiple positions for different sequential assessments, or a tool including multiple probes can be used to perform the assessments simultaneously. For example, in certain embodiments, an instrument having multiple sensor probes is positioned near the spine and near the spinal nerves to detect responses in multiple locations. Each of the sensor probes is located at a different position in the general vicinity of the nerves, at different distances from the nerves. Each probe therefore elicits or receives different responses from the nerves, with respective signal strengths that differ according to the distance from the particular probe to the nerve. For example, a nerve response signal that is greater than a baseline signal by a pre-defined amount corresponds to a stimulation source positioned at a particular distance from the nerve. The known configuration of the probes relative to each other and the different responses elicited by the probes are then used to triangulate the location of the nerve relative to the probes. In systems that monitor both sensory and motor nerves, this neuromonitoring approach provides a map of the nervous anatomy, including both sensory and motor nerves, to provide a surgeon with a more complete map of the anatomy than is obtained by monitoring just one or the other of these two types of nerves.

Locating a nerve using multiple different locations of probes provides data to create a map of the nerve and the path it follows. After moving a probe with multiple sensors to a series of different positions and assessing nerve locations at each position, computer-implemented software processes the information obtained to map the nerve over the distance measured by the multiple locations in which the sensors are positioned. The map traces the nerve in three dimensions and provides a representation of the nerve anatomy that can be used either before, during, or after surgery to reduce the risk of damaging the nerve or assess nerve condition. If each of the probes positioned near the nerves incorporates components for both motor and sensory nerve monitoring, the resulting map can provide a full representation of both the motor and sensory nerves located around the surgical field.

A map of the nerve anatomy near a surgical field provides a helpful pre-surgical planning tool for a surgeon to plan the positioning of instruments for the surgery. As discussed below, the map allows positioning and approach planning to be performed before the actual surgical procedure begins and surgical instruments are advanced to the surgical site. Using the map, a surgeon can plan an approach path for advancing surgical instruments to the desired surgical field while reducing the risk of injuring surrounding nerves. The tools used in the surgery may still include stimulation and detection components for intraoperative monitoring, but the pre-surgical planning is used to further reduce the chance of those tools contacting nerves. In addition, the map may be used to position a probe, retractor, or other instrument in a stationary location known from the map to be near a sensory or motor nerve. The stationary instrument is then used to monitor the particular nerve throughout the surgery as other tools are moved around and used at the surgical site. Changes in the response of the monitored nerve are detected by the stationary instrument and flagged as potentially indicating, for example, impingement, compression, contact, or other injury to the nerve. The map can also be used during a surgical procedure to provide real-time information indicating the location of several nerves relative to a surgical instrument or to the surgical site. Similarly, the map can be used after surgery to provide an assessment of the impact of the surgical procedure on various characteristics of the nerve, such as change in neural physiology or position.

In some implementations, the neuromonitoring techniques described herein are employed during a surgical procedure to detect and guard nerves intraoperatively. For example, neuromonitoring is performed during a spinal surgery in which instruments are advanced to the patient's spine, including surgical approaches for establishing an operative corridor to an intervertebral target site. Such an approach may be used to establish a path to an operative site that is anterior, posterior, or on either side of the spine. For some surgeries, lateral approach may be preferred to gain access to the spine, for example, to access vertebral pedicles or intervertebral discs and to provide advantageous angles for insertion of pedicle screws. Instruments approaching the spine laterally must be advanced with caution, as sensitive nerve roots from the spinal cord exit the spine in lateral directions, and harm or unintentional stimulation of these nerves can cause pain or damage. In order to reduce unwanted contact with these nerves, neuromonitoring described herein may be used to determine the proximity of nerves and warn a surgeon if a surgical instrument is approaching too near to one or more of the nerve roots. By applying stimulus currents to or measuring responses from the nerves in the proximity of the instruments, such neuromonitoring techniques guide a surgeon through the tissue and to the spine without unintentionally contacting or damaging the nerves.

According to one aspect, a method of neuromonitoring includes the steps of delivering a first stimulus signal to a first stimulating electrode disposed at or near a dermatome innervated by a first nerve, receiving a nerve response signal detected by a response sensor disposed in tissue near the first nerve, determining a characteristic of the first nerve based on the nerve response signal, and communicating an indication of the characteristic to a user.

In some implementations, the stimulus is configured by delivering test stimulus signals to a plurality of stimulating electrodes disposed at or near the dermatome. The test stimulus signals may be delivered individually from each of the plurality of stimulating electrodes, and/or may be delivered from combinations of the plurality of stimulating electrodes. Test response signals are detected by the response sensor, and each response signal is associated with one or more of the plurality of stimulating electrodes. The test stimulus signals and test response signals are processed to automatically select stimulating electrodes for neuromonitoring. Processing the test stimulus signals and test response signals may include determining a response latency associated with each of the plurality of stimulating electrodes and/or determining a response amplitude associated with each of the plurality of stimulating electrodes. The method may include selecting stimulating electrodes having the largest response amplitudes.

In some implementations, the method includes synchronizing stimulus signals for the selected stimulating electrodes based on the determined response latencies. For synchronization, a stimulus signal is delivered from a first selected stimulating electrode having the longest response latency, stimulus signals delivered from subsequent selected stimulation electrodes having shorter response latencies are delayed. The stimulus signal delivered from each subsequent stimulation electrode is delayed by the difference between the longest response latency and a response latency associated with the subsequent stimulation electrode.

In some implementations, stimulus delivered from selected stimulation electrodes elicits a nerve response having a higher signal-to-noise ratio than nerve responses elicited by individual stimulation electrodes. The stimulus delivered from the selected stimulation electrodes may also elicit a compound action potential in the first nerve, and the stimulus may be delivered to more than one branch of the first nerve or to more than one dermatome innervated by the first nerve.

In some implementations, the method includes delivering a second stimulus signal to a second stimulating electrode disposed in tissue near a second nerve. A muscle response signal is received from a muscle sensor disposed in or near muscle tissue innervated by the second nerve. The muscle sensor may be placed on a skin surface near the muscle tissue innervated by the second nerve, or may be disposed within the muscle tissue. The second nerve is identified from data associating the muscle tissue with the second nerve. In some implementations, the method includes determining a characteristic of the second nerve based on the muscle response signal.

In some implementations, a surgical instrument is provided with the response sensor and the second stimulating electrode disposed on a distal end of the instrument. The surgical instrument is advanced towards a patient's spine prior to delivering the first stimulus signal. The surgical instrument may be one of a monopolar probe, a tissue dilator, a tissue retractor, a scalpel, a tool for implant placement, a pedicle screw, or a guide wire. The method may include toggling a neuromonitor coupled to the surgical instrument between a motor nerve stimulating state and a sensory nerve detecting state, and may include synchronizing stimulus signals delivered to the first and second stimulating electrodes. The synchronization is done based on latencies associated with the first and second nerves.

According to one aspect, a system for neuromonitoring includes a first stimulating electrode configured to deliver stimulation at or near a dermatome innervated by a first nerve, a nerve sensor configured to detect a nerve response in tissue near the first nerve, and a neuromonitor coupled to the first stimulating electrode and the nerve response sensor, the neuromonitor having processing circuitry. The processing circuitry is configured to deliver a first stimulus signal to the first stimulating electrode, receive a nerve response signal from the nerve sensor, determine a characteristic of the first nerve based on the nerve response signal, and communicate an indication of the characteristic to a user.

In some implementations, the first stimulating electrode and the nerve sensor communicate with the neuromonitor via a wired connection. In other implementations, the first stimulating electrode and the nerve sensor communicate with the neuromonitor via a wireless connection. There may be a plurality of stimulating electrodes coupled to the neuromonitor, and the plurality of stimulating electrodes may be in an electrode array. The processing circuitry is configured to deliver test stimulus signals to the plurality of stimulating electrodes. The processing circuitry may be configured to deliver the test stimulus signals individually to each of the plurality of stimulating electrodes, and/or may be configured to deliver the test stimulus signals to combinations of the plurality of stimulating electrodes. The nerve sensor is configured to detect test response signals associated with one or more of the plurality of stimulating electrodes. The processing circuitry is configured to automatically select stimulating electrodes for neuromonitoring from the test stimulus signals and test response signals.

In some implementations, the processing circuitry is configured to determine a response latency associated with each of the plurality of stimulating electrodes and is configured to determine a response amplitude associated with each of the plurality of stimulating electrodes. The processing circuitry is configured to select stimulating electrodes having the largest response amplitudes.

In some implementations, the processing circuitry is configured to synchronize stimulus signals for the selected stimulating electrodes based on the determined response latencies. The processing circuitry is configured to deliver a stimulus signal to a first selected stimulating electrode having the longest response latency and delay stimulus signals delivered to subsequent selected stimulation electrodes having shorter response latencies. The processing circuitry is configured to calculate the difference between the longest response latency and the response latency associated with each subsequent stimulation electrode, and is configured to delay stimulus signals delivered to each subsequent stimulation electrode by the calculated difference associated with the respective subsequent stimulation electrode.

In some implementations, the processing circuitry is configured to select a combination of stimulation electrodes that elicits a nerve response having a higher signal-to-noise ratio than nerve responses elicited by individual stimulation electrodes and/or is configured to select a combination of stimulation electrodes that elicits a compound action potential in the first nerve. In some implementations, the system includes a second stimulating electrode configured to deliver stimulation in tissue near a second nerve The processing circuitry is configured to deliver a second stimulus signal to the second stimulating electrode, and a muscle sensor configured to detect a muscle response signal in or near muscle tissue innervated by the second nerve. The muscle sensor comprises may be a needle electrode or a skin electrode. The processing circuitry is configured to identify the second nerve from data associating the muscle tissue with the second nerve, and the processing circuitry is configured to determine a characteristic of the second nerve based on the muscle response signal.

In some implementations, the system includes a surgical instrument, wherein the response sensor and the second stimulating electrode are disposed on a distal end of the instrument. The surgical instrument may be one of a monopolar probe, a tissue dilator, a tissue retractor, a scalpel, a tool for implant placement, a pedicle screw, or a guide wire. The neuromonitor is configured to toggle between a motor nerve stimulating state and a sensory nerve detecting state, and is configured to synchronize stimulus signals delivered to the first and second stimulating electrodes.

According to one aspect, a system for neuromonitoring includes means for delivering a first stimulus signal at or near a dermatome innervated by a first nerve, means for receiving a nerve response signal in tissue near the first nerve means for determining a characteristic of the first nerve based on the nerve response signal and means for communicating an indication of the characteristic to a user.

In some implementations, the system includes means for delivering test stimulus signals at or near the dermatome. The test stimulus signals may be delivered individually from each of a plurality of stimulating means, or may be delivered from combinations of stimulating means. The system includes means for receiving test response signals, wherein each response signal is associated with one or more stimulating means.

In some implementations, the system includes means for processing the test stimulus signals and test response signals to automatically select stimulating means for neuromonitoring. The system may also include means for determining a response latency associated with each of the plurality of stimulating means, and means for determining a response amplitude associated with each of the plurality of stimulating system. Means for selecting stimulating means having the largest response amplitudes are also provided. The system may include means for synchronizing stimulus signals for the selected stimulating means based on the determined response latencies, means for delivering a stimulus signal from a first selected stimulating means having the longest response latency, and means for delaying stimulus signals delivered from subsequent selected stimulation means having shorter response latencies. The stimulus signal delivered from each subsequent stimulation means is delayed by the difference between the longest response latency and a response latency associated with the subsequent stimulation means.

In some implementations, stimulus delivered from the selected stimulation electrodes elicits a nerve response having a higher signal-to-noise ratio than nerve responses elicited by individual stimulation electrodes, and stimulus delivered from the selected stimulation means may elicit a compound action potential in the first nerve, or may be delivered to more than one branch of the first nerve or to more than one dermatome innervated by the first nerve.

In some implementations, the system includes means for delivering a second stimulus signal to a second stimulating means disposed in tissue near a second nerve and means for receiving a muscle response signal detected by a muscle sensor means disposed in or near muscle tissue innervated by the second nerve. The muscle sensor means may be a skin surface placed near the muscle tissue innervated by the second nerve. The system includes means for identifying the second nerve from data associating the muscle tissue with the second nerve and means for determining a characteristic of the second nerve based on the muscle response signal.

In some implementations, the system includes an instrument means having the means for receiving a nerve response signal in tissue near the first nerve and the second stimulating means disposed on a distal end of the instrument means. A means for advancing the instrument means is provided to advance the instrument means towards a patient's spine prior to delivering the first stimulus signal. The instrument means may be one of a monopolar probe, a tissue dilator, a tissue retractor, a scalpel, a tool for implant placement, a pedicle screw, or a guide wire. In some implementations, the system includes means for toggling a neuromonitor coupled to the instrument means between a motor nerve stimulating state and a sensory nerve detecting state. and means for synchronizing stimulus signals delivered to the first and second stimulating means.

According to one aspect, a method of mapping nerve anatomy includes delivering stimulus to a first stimulating electrode disposed at or near a dermatome innervated by a first nerve, receiving a plurality of nerve response signals detected at response sensor positions in tissue near the first nerve, calculating a distance from each response sensor position to the first nerve determining, based on the calculated distances, a location of the first nerve, and plotting the determined location of the first nerve.

In some implementations, the method includes providing a probe having a response sensor disposed on a distal end of the probe, positioning the distal end of the probe at each of the response sensor positions in the tissue near the first nerve, and detecting a nerve response signal at the response sensor at each of the response sensor positions. A second stimulating electrode may also be disposed on the distal end of the probe.

In some implementations, the method includes providing a probe having a plurality of probe ends, each probe end having a response sensor, positioning the probe at a first probe position, wherein the plurality of probe ends are positioned at different response sensor positions when the probe is in a first probe position, and detecting a nerve response at each of the response sensors after stimulus is delivered to the first stimulating electrode. A distance is calculated from each probe end to the first nerve when the probe is positioned at the first probe position, and the distances calculated when the probe is positioned at the first probe position are processed to determine a first location of the first nerve. The probe is positioned at a second probe position, wherein each of the probe ends are positioned at different response sensor positions relative to the response sensor positions when the probe is in the first probe position. A nerve response is detected at each of the response sensors after stimulus is delivered to the first stimulating electrode, and a distance is calculated from each probe end to the first nerve when the probe is positioned at the second probe position. The distances calculated when the probe is positioned at the second probe position are processed to determine a second location of the first nerve. In some implementations, additional stimulating electrodes are provided, each additional stimulating electrode disposed on a respective one of the probe ends.

In some implementations, the method includes calculating distances from each response sensor position to the first nerve based on at least one of stimulation current, stimulation frequency, stimulation voltage, response amplitude, response latency, response frequency, and response direction. The method may also include calculating a direction from each response sensor position to the first nerve.

In some implementations, each determined location is associated with the first nerve. A location may be associated with the first nerve based on the stimulated dermatome, or may be associated with the first nerve based on user input or based on data stored in memory at a neuromonitor. The stored data may identify a relation between the first nerve and the first stimulating electrode, and/or the stored data may identify a relation between the stimulated dermatome and the first nerve.

In some implementations, the method includes storing a plurality of determined locations of the first nerve in memory at a neuromonitor and updating the stored locations with each subsequent location determined for the first nerve. The stored locations are plotted in a three-dimensional space, and the plot is displayed to a user.

According to one aspect, a system for mapping nerve anatomy includes a first stimulating electrode configured to deliver stimulation at or near a dermatome innervated by a first nerve, at least one response sensor configured to detect a nerve response at response sensor positions in the tissue near the first nerve, and a neuromonitor coupled to the first stimulating electrode and the at least one response sensor, the neuromonitor having processing circuitry. The processing circuitry is configured to calculate a distance from each response sensor position to the first nerve, determine, based on the calculated distances, a location of the first nerve, and plot the determined location of the first nerve.

In some implementations, the system includes a probe having a response sensor disposed on a distal end of the probe, and may include a second stimulating electrode disposed on the distal end of the probe.

In some implementations, the system includes a probe having a plurality of probe ends, each probe end having a response sensor. Each of the plurality of probe ends is positioned at a different response sensor positions when the probe is in a first probe position, and the response sensors are configured to detect a nerve response after stimulus is delivered to the first stimulating electrode. The processing circuitry is configured to calculate a distance from each probe end to the first nerve when the probe is positioned at the first probe position, and the processing circuitry is configured to determine a first location of the nerve based on the calculated distances. Each of the plurality of probe ends is positioned at a different response sensor position when the probe is positioned at a second probe position relative to the response sensor positions when the probe is in the first probe position, and the response sensors are configured to detect a nerve response after stimulus is delivered to the first stimulating electrode. The processing circuitry is configured to calculate a distance from each probe end to the first nerve when the probe is positioned at the second probe position. The processing circuitry is configured to determine a second location of the first nerve based on the distances calculated when the probe is positioned at the second probe position. In some implementations, the system includes additional stimulating electrodes, each additional stimulating electrode disposed on a respective one of the probe ends.

In some implementations, the processing circuitry is configured to calculate distances from each response sensor position to the first nerve based on at least one of stimulation current, stimulation frequency, stimulation voltage, response amplitude, response latency, response frequency, and response direction. The processing circuitry may also be configured to calculate a direction from each response sensor position to the first nerve. The processing circuitry is configured to associate each determined location with the first nerve. The processing circuitry may be configured to associate a location with the first nerve based on the stimulated dermatome, based on user input, and/or based on data stored in memory at the neuromonitor. The stored data identifies a relation between the first nerve and the first stimulating electrode or between the stimulated dermatome and the first nerve.

In some implementations, the neuromonitor is configured to store a plurality of determined locations of the first nerve in memory. The processing circuitry is configured to update the stored locations with each subsequent location determined for the first nerve and is configured to plot the stored locations in a three-dimensional space. The system may include a display configured to display a plot of the stored locations to the user.

According to one aspect, a system of mapping nerve anatomy includes means for delivering stimulus at or near a dermatome innervated by a first nerve, means for receiving a plurality of nerve response signals at response positions in tissue near the first nerve, means for calculating a distance from each response position to the first nerve, means for determining, based on the calculated distances, a location of the first nerve, and means for plotting the determined location of the first nerve.

In some implementations, the system includes probe means having a means for detecting a nerve response disposed on a distal end of the probe means. The system includes means for positioning the distal end of the probe means at each of the response positions in the tissue near the first nerve and means for detecting a nerve response signal at the means for detecting a nerve response at each of the response sensor positions. In some implementations, a second stimulating means is disposed on the distal end of the probe means.

In some implementations, the system includes a probe means having a plurality of probe ends, each probe end having a means for detecting a nerve response and means for positioning the probe means at a first probe position, wherein the plurality of probe ends are positioned at different response positions when the probe means is in a first probe position. The system includes means for detecting a nerve response at each of the response positions after stimulus is delivered to the first stimulating means. Means are provided for calculating a distance from each probe end to the first nerve when the probe means is positioned at the first probe position, and for processing the distances calculated when the probe means is positioned at the first probe position to determine a first location of the first nerve.

In some implementations, the system includes means for positioning the probe means at a second probe position, wherein each of the probe ends are positioned at different response positions relative to the response positions when the probe means is in the first probe position. Means are provided for detecting a nerve response at each of the response positions after stimulus is delivered to the first stimulating means, and for calculating a distance from each probe end to the first nerve when the probe means is positioned at the second probe position. Means for processing the distances calculated when the probe means is positioned at the second probe position are used to determine a second location of the first nerve. In some implementations, the system includes additional stimulating means, each additional stimulating means disposed on a respective one of the probe ends.

In some implementations, the system includes means for calculating distances from each response position to the first nerve based on at least one of stimulation current, stimulation frequency, stimulation voltage, response amplitude, response latency, response frequency, and response direction. The system may also include means for calculating a direction from each response position to the first nerve. The system includes means for associating each determined location with the first nerve, and may include means for associating a location with the first nerve based on the stimulated dermatome, based on user input, and/or based on data stored in memory at a neuromonitor. The stored data identifies a relation between the first nerve and the first stimulating means, and may identify a relation between the stimulated dermatome and the first nerve.

In some implementations, the system includes means for storing a plurality of determined locations of the first nerve in memory at a neuromonitor and means for updating the stored locations with each subsequent location determined for the first nerve. Means are provided for plotting the stored locations in a three-dimensional space, and the system may include means for displaying a plot of the stored locations to a user.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects and advantages will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout.

FIG. **1** shows a neuromonitoring system.

FIG. **2** shows a block diagram of a neuromonitoring system

FIG. **3** shows anatomy of the spine and spinal nerves.

FIG. **4** shows a stimulus profile and response signal during neuromonitoring of a sensory spinal nerve.

FIG. **5** shows a stimulus profile and response signal during neuromonitoring of an injured sensory spinal nerve.

FIG. **6** shows a stimulus profile and response signal during neuromonitoring of a compressed spinal nerve.

FIG. **7** shows a stimulus profile having pulses with increasing intensities and a corresponding response signal.

FIG. **8** shows a stimulus profile and response signal of a below-threshold sensory spinal nerve response.

FIG. **9** shows stimulus profiles and a response signal of a sensory spinal nerve exhibiting different response latencies in the response signal.

FIG. **10** shows stimulus profiles and a response signal of synchronized stimulation pulses creating a compound action potential.

FIG. **11** shows stimulus profiles and a response signal for synchronized motor and sensory nerve monitoring.

FIGS. **12**-**14** show a system for mapping nerve anatomy.

FIG. **15** shows a computing device.

DETAILED DESCRIPTION

To provide an overall understanding of the systems, devices and methods disclosed herein, certain illustrative embodiments will be described. Although the embodiments and features described herein are specifically discussed for use in connection with spinal surgical procedures, it will be understood that the system components, connection mechanisms, surgical procedures, neuromonitoring, and other features outlined below may be combined with one another in any suitable manner and may be adapted and applied to systems to be used in other surgical procedures performed in the proximity of neural structures where nerve avoidance, detection, or mapping is desired, including but not limited to spine surgeries, brain surgeries, carotid endarterectomy, otolaryngology procedures such as acoustic neuroma resection, parotidectomy, nerve surgery, or any other surgical procedures in which nerve injury is possible and nerve preservation is desirable.

The systems, devices and methods disclosed herein relate to intraoperative neuromonitoring of evoked potential, transcranial electrical motor evoked potential, electromyography, and electroencephalogram signals. Intraoperative neuromonitoring reduces the risk of injury to neural structures during surgical procedures. Changes or abnormalities in the recording signals may indicate that the surgical procedure is affecting the neural structure being monitored. A monitoring system displays the electrical signals generated by one or more muscles, the central nervous system, and peripheral nerves and acquires the data necessary to perform intraoperative monitoring of neural pathways to prevent damage to neural structures during surgical procedures. It will be appreciated that the systems, devices and methods of the present disclosure can be adapted for use in pre- and post-operative procedures in addition to or in place of intraoperative procedures. In particular, the systems, methods, and devices described herein may be employed in any surgical procedure where pre-surgical planning, intraoperative monitoring, or post-operative evaluation of sensory or motor nerves would be beneficial, including, for example procedures that employ a lateral, posterior, or anterior approach to any portion of the thoracic or lumbar spine.

The neuromonitoring systems described herein provide pre-surgical planning and intraoperative monitoring by integrating neuromonitoring electrodes and sensors into the tools used during surgery and connecting those tools to electrical sources. Such tools may include tools used for approaching and creating a path to a surgical target, for example the spine. Approach tools may include scalpels, tissue dissection tools, guide wires, needles (e.g., needles having an insulated shaft and an exposed tip), dilators (including sequential dilation systems), retractors, working cannula, monopolar or bipolar probes, or any other surgical tools used to begin, create, or maintain a path to the surgical site. In some surgeries, the path to the surgical site is created and maintained using these surgical tools in sequence. For example, in some surgeries, an initial path is started using a scalpel or other tool for removing and cutting tissue near the skin surface. A guidewire is then advanced through the incision and, under the guidance of intraoperative imaging, advanced toward the surgical site to provide the path over which subsequent tools are advanced. Because it is the first tool advanced into deep tissue in some surgeries, providing neuromonitoring implements on the distal end of the guidewire may be preferable. Once the guidewire is placed, one or more dilators are advanced over the guidewire to widen the path through the tissue, and each sequential dilator may include neuromonitoring electrodes and sensors to protect neural tissue as the path is widened. Once the path is created, tissue retractors or working cannula are then used to maintain the path created by the dilators and provide access to the surgical site for the operation.

The electrodes and sensors used for neuromonitoring are provided on these tools to give early assessment and warnings as the tools are advanced into a patient's tissue. The tools are also used to provide intraoperative neuromonitoring during a surgery after the path to the surgical site is created. For example, working cannula, retractors, or stationary probes that hold tissue during surgery may monitor nearby nerve structures throughout the surgical procedure as other instruments are advanced to the surgical site and used. This provides ongoing monitoring after the initial path to the surgical site has been created, and can be used to monitor the neural structures while other instruments that may or may not include electrodes or sensors are used in the surgery.

In addition to guarding surrounding nerves from damage as tools are advanced to the spine and used in an operation, the surgical tools described herein include tools that provide intraoperative monitoring of the efficacy of a surgical procedure. Such tools include electrified probes, pedicle screws, pedicle screw placement tools, interbody implants, interbody implant placement tools, and any other tools that are used to carry out the procedure at the surgical site. These tools are used to evaluate the accuracy and efficacy of instrument placement, pedicle tapping, screw placement, pedicle integrity, interbody preparation, and interbody implant placement. The tools guard against complications that can arise when the surgical tools compromise the anatomical structures being operated on, for example when a drilling tool or screw compromises the wall of a tapped pedicle hole.

FIG. **1** shows an illustrative system for surgical neuromonitoring. During a surgical procedure, an instrument **4** is advanced towards a patient's spine from the lateral aspect of the patient's body while neuromonitoring is performed to detect and signal the presence of nerves in the patient's tissue as the instrument **4** is advanced deeper into the body. The instrument **4** may be any suitable electrified surgical instrument, for example a monopolar probe, a tissue dilator (which may be tubular or non-tubular), a tissue retractor, working cannula, a scalpel, a needle, a tool for implant placement, a pedicle screw, a guide wire, a sequential access surgical system including multiple instruments, or any other surgical instrument that may be used in spinal surgery. The instrument **4** can also provide nerve monitoring and detection after it is advanced to the surgical site, as may be the case with, for example, a pedicle probe used to drill or implant a pedicle screw at the site. When the instrument **4** is used to create an operative corridor, the instrument **4** may be directed through the psoas muscle during the procedure, although the instrument can also be used in approaches involving retraction of the psoas muscle using an electrified retractor, cannula, or other instruments.

One or more neuromonitoring components are disposed on the distal end **16** of the instrument **4**. The components include response sensors (e.g., sensory electrodes) that sense nerve responses from nerves in the proximity of distal end **16** when those nerves are stimulated by stimulus signals delivered elsewhere, for example to sensory tissue. The response sensors detect electrical signals in the vicinity of the instrument **4**. The sensors detect changes in the body's electrical potential in tissue surrounding the instrument **4**, for example when a nerve in the vicinity of the instrument is stimulated and depolarizes. The depolarization of the nerve caused by a propagating nerve signal, or action potential, and subsequent repolarization of the nerve is detected by the response sensor and can be seen in a graph of the electrical potential detected by the instrument over time. As discussed below, the components on the distal end **16** may also include stimulating electrodes that deliver electrical signals to stimulate nerves in the proximity of the instrument **4**, for example when the system is used to monitor both sensory and motor nerves.

During neuromonitoring, stimulations delivered to nerve responses are controlled and processed by the neuromonitor **2**. The neuromonitor **2** preferably includes one or more suitable programmable processor-based devices (each having one or more processors) that include processing circuitry for controlling the neuromonitor and/or the surgical system. The neuromonitor **2** may include stimulation circuitry (not shown), which may be embodied as a separate stimulation device connected to the neuromonitor **2** by a cable or wireless connection, or which may be embedded within the housing of neuromonitor **2**. The stimulation circuitry works together with neuromonitor **2** to send stimulation signals to the one or more stimulation electrodes. The neuromonitor **2** also includes stimulation processing circuitry that controls the stimulation sources (e.g., by controlling the amplitude, duration, or frequency of stimulation signals). The stimulation circuitry (and/or neuromonitor **2**) may include external controls that allow a user to start, stop, or adjust the stimulation signals. The neuromonitor **2** also includes response circuitry (not shown), which may be embodied as a separate response device connected to the neuromonitor **2** by a cable or wireless connection, or which may be embedded within the housing of neuromonitor **2**. In preferred implementations, the response circuitry and the stimulation circuitry are located in the same device (e.g., in neuromonitor **2**). The response circuitry receives digitized signals and other information from the stimulation circuitry indicative of the stimulations delivered to a patient, and (alone or in cooperation with neuromonitor **2**) processes the received signals (which may be EMG, EEG, or other suitable signal) to extract characteristic information for each muscle group or nerve.

The neuromonitor **2** includes hardware and software platforms that control, send, receive, and process the stimulation signals, detected responses, and other communications during the neuromonitoring process. Included in the neuromonitor **2** is at least one processor or other circuitry that is configured with one or more algorithms for calibrating the neuromonitoring system, generating stimulus pulses, filtering signals, applying mathematical processes to analyze received signals, or performing other functions during the neuromonitoring process. These processes configure delivered stimulations, for example by selecting stimulating electrodes or timing stimulation pulses, control stimulating electrodes to deliver the stimulation pulses, filter signals from the electrodes and from response sensors, process one or more features of the stimulations and responses to analyze nerve anatomy, and communicate indications relating to the nerve anatomy. The neuromonitor **2** may receive user input, for example from a surgeon configuring the system, to control or change one or more of the functions carried out by the neuromonitor processing circuitry. To provide this processing power, the neuromonitor **2** may include one or more pieces of neuromonitoring equipment that act together to perform the neuromonitoring functions. For example, the neuromonitor **2** may include a Cadwell Cascade® neuromonitoring unit, or any other suitable neuromonitoring equipment made by Cadwell Laboratories, Inc.

FIG. **15** is a block diagram of a computing device **600**, which may be a component of the neuromonitor **2** or any of the neuromonitors discussed herein, for performing any of the processes described herein. In certain implementations, a plurality of the components of these neuromonitoring systems may be included within one computing device **600**. In certain implementations, components may be implemented across several computing devices **600**.

The computing device **600** includes at least one communications interface unit, an input/output controller **610**, system memory, and one or more data storage devices. The system memory includes at least one random access memory (RAM **602**) and at least one read-only memory (ROM **604**). All of these elements are in communication with a central processing unit (CPU **606**) to facilitate the operation of the computing device **600**. The computing device **600** may be configured in many different ways. For example, the computing device **600** may be a conventional standalone device or alternatively, the functions of computing device **600** may be distributed across multiple devices. In FIG. **15**, the computing device **600** is linked, via network or local network, to other servers or devices.

The computing device **600** may be configured in a distributed architecture, wherein databases and processors are housed in separate units or locations. Some units perform primary processing functions and contain at a minimum a general controller or a processor and a system memory. In distributed architecture implementations, each of these units may be attached via the communications interface unit **608** to a communications hub or port (not shown) that serves as a primary communication link with other servers and other related devices. The communications hub or port may have minimal processing capability itself, serving primarily as a communications router. A variety of communications protocols may be part of the system, including, but not limited to: Ethernet, SAP, SAS™, ATP, BLUETOOTH™, GSM and TCP/IP.

The CPU **606** comprises a processor, such as one or more conventional microprocessors and one or more supplementary co-processors such as math co-processors for offloading workload from the CPU **606**. The CPU **606** is in communication with the communications interface unit **608** and the input/output controller **610**, through which the CPU **606** communicates with other devices such as other servers or neuromonitors. The communications interface unit **608** and the input/output controller **610** may include multiple communication channels for simultaneous communication with, for example, other processors, servers, neuromonitors, or other computing devices.

The CPU **606** is also in communication with the data storage device. The data storage device may comprise an appropriate combination of magnetic, optical or semiconductor memory, and may include, for example, RAM **602**, ROM **604**, flash drive, an optical disc such as a compact disc or a hard disk or drive. The CPU **606** and the data storage device each may be, for example, located entirely within a single neuromonitor or other computing device; or connected to each other by a communication medium, such as a USB port, serial port cable, a coaxial cable, an Ethernet cable, a telephone line, a radio frequency transceiver or other similar wireless or wired medium or combination of the foregoing. For example, the CPU **606** may be connected to the data storage device via the communications interface unit **608**. The CPU **606** may be configured to perform one or more particular processing functions.

The data storage device may store, for example, (i) an operating system **612** for the computing device **600**; (ii) one or more applications **614** (e.g., computer program code or a computer program product) adapted to direct the CPU **606** in accordance with the systems and methods described here; or (iii) database(s) **616** adapted to store information that may be utilized to store information required by the program.

The operating system **612** and applications **614** may be stored, for example, in a compressed, an uncompiled and an encrypted format, and may include computer program code. The instructions of the program may be read into a main memory of the processor from a computer-readable medium other than the data storage device, such as from the ROM **604** or from the RAM **602**. While execution of sequences of instructions in the program causes the CPU **606** to perform the process steps described herein, hard-wired circuitry may be used in place of, or in combination with, software instructions for implementation of the processes of the present invention. Thus, the systems and methods described are not limited to any specific combination of hardware and software.

A neuromonitor may incorporate a "computer-readable medium," which refers to any non-transitory medium that provides or participates in providing instructions to the processor of the computing device **600** (or any other processor of a device described herein) for execution. Such a medium may take many forms, including but not limited to, non-volatile media and volatile media. Non-volatile media include, for example, optical, magnetic, or opto-magnetic disks, or integrated circuit memory, such as flash memory. Volatile media include dynamic random access memory (DRAM), which typically constitutes the main memory. Common forms of computer-readable media include, for example, a floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD, any other optical medium, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a PROM, an EPROM or EEPROM (electronically erasable programmable read-only memory), a FLASH-EEPROM, any other memory chip or cartridge, or any other non-transitory medium from which a computer can read.

Various forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to the CPU **606** (or any other processor of a device described herein) for execution. For example, the instructions may initially be borne on a magnetic disk of a remote computer (not shown). The remote computer can load the instructions into its dynamic memory and send the instructions over an Ethernet connection, cable line, or even telephone line using a modem. A communications device local to a computing device **600** (e.g., a server) can receive the data on the respective communications line and place the data on a system bus for the processor. The system bus carries the data to main memory, from which the processor retrieves and executes the instructions. The instructions received by main memory may optionally be stored in memory either before or after execution by the processor. In addition, instructions may be received via a communication port as electrical, electromagnetic or optical signals, which are exemplary forms of wireless communications or data streams that carry various types of information.

The neuromonitor **2** may incorporate any one or more of the hardware and software components described above with respect to computing device **600**. These components provide processing logic in the neuromonitor that controls stimulations, processes responses, and carries out nerve detection using the surgical instrument **4**. The instrument **4** is coupled to the neuromonitor **2** by a wired connection **18**. In alternative embodiments, a wireless neuromonitor and wireless surgical instrument are used instead of the wired connection **18**. The neuromonitor **2** controls stimulation and monitors nerve response detection and processing for the system shown in FIG. **1**. In particular, the neuromonitor **2** controls the delivery of stimulus signals to stimulating electrodes in contact with the patient's body and receives detected signals from response sensors on the instrument **4** or from other sensors. The neuromonitor **2** controls the stimulation and processes the received response signals in order to determine characteristics of nerves in the vicinity of the distal end **16** of the instrument **4**. The nerve characteristics monitored by the neuromonitor **2** may include one or more of the distance between the instrument and the nerve, the direction from the instrument to the nerve, the amplitude of the nerve response, the latency of the nerve response, nerve integrity, nerve location, or any other suitable characteristic. For some determinations, for example calculating distance to a nerve, the processor of the neuromonitor **2** is programmed to calculate the particular characteristic from the stimulus delivered, the nerve response detected, or both.

The neuromonitor **2** outputs determined information to a surgical display **8**. The surgical display **8** provides a surgeon with indications of the characteristics derived from the detected signals received by the neuromonitor **2** to guide surgery. This information may be a display of raw signal, such as an EMG signal, an indication of nerve proximity, an indication of nerve integrity, an indication of nerve direction, an indication of the position of the surgical instrument **4**, or any other suitable characteristics determined from the delivered stimulation and the detected nerve responses, including indicating within which of several ranges the detected value for each of these parameters may fall. Although one neuromonitor **2** is shown in FIG. **1** for ease of discussion, the neuromonitor **2** may include multiple neuromonitor apparatus working together in a centralized or decentralized fashion, including units that may be located remotely from the surgical site. For example, a first neuromonitor located within physical proximity of the surgical site may be used to provide stimulation signals to the neuromonitoring components and to receive responses from the response sensors. The responses may be transmitted over a wireless and/or wired link to a second neuromonitor that processes the responses and provides feedback to one or more clinicians or monitorists associated with the surgical procedure via one or more communication outputs, such as surgical display **8**.

The display **8** communicates neuromonitoring information to the surgeon to operator (e.g., a surgeon or a monitorist). The display unit is equipped with a graphical user interface for providing information regarding any of the monitored characteristics visually to the operator. In addition or in the alternative, the display **8** controls audio components to communicate information audibly to the user, such as by changing the pitch or volume of an audio output based on whether the characteristic is within safe zones or warning zones. In some embodiments, the display **8** provides an alarm to warn the operator of potential injury to the nerve. The information may be provided in any suitable manner to the surgeon, including displaying indicators or warnings on the screen, displaying sensor signals, displaying electrode stimulus profiles, identifying the sensory or motor nerves monitored based on the sensory tissue stimulated or the muscle response detected, providing alphanumeric indicators of one or more nerve characteristics, displaying graphical indications of instrument or nerve location, and displaying a neural map, which may include an anatomical representation of the human form. The information and indicators may be color-coded, for example to differentiate a safe reading or circumstance from one that is potentially harmful to the patient. For example, when a threshold stimulation current is determined for a nerve in the vicinity of the surgical tool, the display **8** may provide an indication to the surgeon of the determined threshold that is color-coded based on a range that the threshold falls within. Such ranges may include preset or surgeon-manipulated safe and unsafe ranges of currents. The display **8** may be a touch-based communication interface capable of receiving input from the operator and providing the input to the neuromonitor **2**. Only one display **8** is shown in FIG. **1**. However, in some implementations, the system includes multiple displays (up to 2, up to 3, up to 5, up to 10, or up to 100) for simultaneously providing information to various users. One or more of the multi-display systems and methods discussed therein may be used in combination with any of the systems and methods described herein, including for displaying characteristics associated with sensory nerves. The display may include multiple displays, and may portray indications and information of sensory and motor nerve status similar to those discussed with respect to motor nerve monitoring in U.S. Provisional Application Nos. 61/721,482, 61/796,207, and 61/730,202, which are hereby fully incorporated by reference herein.

In some implementations, the instrument **4** is a multiple-probe instrument used to analyze and map the nerve anatomy before surgery. In such implementations, the display **8** provides the mapped anatomy to the surgeon. The data used to create the map is obtained by positioning the instrument **4** in multiple positions to determine multiple locations of the mapped nerves. The display **8** may display the developing map to the surgeon as a nerve location is added at each position of the instrument **4**. The surgeon can use the developing map to position the probes for subsequent data acquisition in areas of the nerve that are not yet mapped. The finished map is then used to plan a surgical approach and/or is displayed to guide the surgeon when instruments are advanced to and used at the surgical site during the procedure. In addition to showing the developed map of the anatomy, the display **8** may overlay an approach path planned during the pre-surgical planning to guide the angles and depths at which the surgeon advances various instruments. The map on the display **8** may also be used to position probes near individual nerves for intraoperative monitoring. The display **8** may also track and display the position of the surgical tools relative to the mapped nerves intraoperatively, providing a single view of the mapped nerves and tool positioning to orient the surgeon.

During intraoperative neuromonitoring after the surgical procedure begins, the instrument **4** is used to monitor and detect locations and changes in conditions of sensory nerves, and the sensory nerves monitored may include the genitofemoral nerve shown in FIG. **1**. The genitofemoral nerve has two main branches that pass through the psoas major muscle **13** on the lateral side of the spine. The main branches include a lateral femoral branch **10** and a medial genital branch **11**. During a lateral surgical approach, the instrument **4** is advanced towards the patient's spine from a lateral insertion point and is at risk of compressing or damaging the two branches **10** and **11**. In order to warn a surgeon and reduce the risk of causing such damage, the instrument **4** monitors for nerves as it is advanced by detecting nerve responses from sensory nerves in the vicinity of the instrument.

Because the genitofemoral nerve is a sensory nerve, and not a mixed nerve or motor nerve, the instrument **4** does not monitor for the branches **10** and **11** by delivering stimulus near the nerve and detecting elicited EMG responses, as is done in some motor nerve monitoring approaches. Instead, stimulation is delivered at peripheral locations (either on the patient's skin or by use of subdermal needles or probes) where one or both of the branches **10** and **11** innervate a dermatome near the surface of the skin, for example near the patient's thigh. The system then monitors a response by detecting fluctuations in body potential near an instrument at the spine that signal an action potential propagating in a nearby sensory nerve. In addition to positioning instruments at the spine, a sensory nerve monitoring system may detect the propagating action potential at any point between the stimulated tissue and the brain. For example, the action potential may be sensed by a probe positioned between the spine and the stimulated tissue, near the nerve root exiting the spine, near the spinal cord, at the brain, or on the patient's head.

The stimulation that elicits the detected sensory nerve response is delivered by the electrode array **12** shown connected to the neuromonitor **2** by the connection **20**. While the array **12** is shown with a wired connection, as with the instrument **4**, the electrode array **12** may operate wirelessly and communicate with the neuromonitor **2** over a wireless connection. When the array **12** is placed on a dermatome innervated by the branches **10** or **11**, the delivery of electrical signals to the patient through one or more of the individual stimulating electrodes **14** in the array **12** triggers a sensory response from the corresponding branch **10** or **11** of the genitofemoral nerve. This stimulation causes an electrical signal to propagate from the dermatome through the corresponding branch **10** or **11** to the spinal cord and then to the patient's brain. In order to monitor for the genitofemoral nerve and detect the proximity of the instrument **4** to the nerve, one or more of the sensors on the distal end **16** of instrument **4** senses an electrical response from the genitofemoral nerve when the instrument is at or near one of the branches **10** or **11**. The electrical response of the nerve is measured as an action potential by the sensors on the instrument **4**. The measured potential is the result of the nerve depolarizing and repolarizing as the triggered nerve signal propagates through the nerve from the sensory tissue towards the brain.

The precise location of the dermatome innervated by the genitofemoral nerve and the nerve endings that innervate the dermatome may vary from patient to patient and may not be known for a particular patient. To provide customizable delivery of stimulation to the innervated dermatome, a plurality of the stimulating electrodes **14** are included in the array **12** to allow multiple electrode configuration options for delivering stimulation. For example, any one of the electrodes **14** may be selected to deliver the stimulation to the dermatome, or a combination of the electrodes **14** may be selected by the neuromonitor **2**, or by a surgeon, to deliver the stimulation. The exact combination and location of the electrodes **14** used to deliver the stimulation can be selected through calibration of the system, and the neuromonitor **2** can be programmed to select the combination in an initial stimulation test. In such a stimulation test, the neuromonitor **2** causes multiple combinations of the electrodes **14** in the array **12** deliver test stimulus signals. Sensors on the distal end **16** of the instrument **4** monitor for nerve responses, and once nerve responses are received for multiple combinations of the electrodes **14**, the neuromonitor **2** processes the responses and selects the combination that creates the clearest nerve response for stimulation during further neuromonitoring.

The neuromonitor **2** selects the combination of stimulating electrodes **14** used to deliver stimulation in order to produce a large, detectable response from the sensory nerves that are monitored. Selecting a certain combination of electrodes, and configuring the timing of the stimulation delivered from each, can create a compound action potential within the monitored sensory nerve that produces a more easily detected response than stimulation delivered from any one individual electrode. Stimulation from each individual electrode may elicit a nerve response from a monitored nerve that has a different amplitude or reaches a sensory probe upstream near the nerve at a slightly different timing than stimulation delivered from the other electrodes. The electrodes that elicit the strongest responses are selected for monitoring, and the timing of stimulation delivered from those electrodes is adjusted to coordinate the arrival of the action potential responses at the stimulus probe. The resulting aggregate of the individual responses, or compound action potential, produces a greater electrical signal for detecting than any of the individual electrodes produces. Timing approaches are discussed in further detail below with respect to FIGS. **8-11**.

In addition to timing signals and creating a compound action potential, stimulation from multiple electrodes **14** in the array **12** can improve the detectability of signals by stimulating different branches of a nerve, or stimulating different dermatomes innervated by the nerve. Nerve endings include many fibers that innervate tissue, for example a sensory dermatome. Stimulating different areas of that tissue can stimulate different branches of the nerve ending. The stimulation of multiple nerve branches creates multiple small nerve responses in the branches that aggregate to form a larger response signal that propagates through the nerve, producing a larger detectable signal at an upstream response sensor. Similarly, nerves that innervate more than one sensory tissue, like the genitofemoral nerve, produce a larger aggregate response signal when more than one of the innervated tissues is stimulated. In addition to selecting multiple electrodes for stimulation, as discussed below, the stimulation provided to multiple nerve branches or multiple dermatomes of a nerve can be timed to create an aggregate signal that reaches the probe at the same time.

The nerve signal produced by stimulation provided at more than one electrode may also be amplified by creating a current density between electrodes that stimulates the main branch of the sensory nerve within the tissue, rather than stimulating only endings of the nerve. The location of the electrodes, and the intensity of the stimulation delivered to stimulate the main branch, will likely vary from nerve to nerve and patient to patient. To stimulate the main branch, two or more electrodes are positioned spaced apart such that the main branch is positioned within the tissue between the electrodes. When stimulation is delivered at the electrodes, a current density is created between the locations of the electrodes. If the current density is great enough, the nerve branch between the electrodes is triggered by the density between them, and the resulting signal that propagates through the nerve is larger than a compound action potential created by stimulating nerve endings at each of the electrodes individually. The stimulation delivered from each electrode may need to be increased, for example to double, three times, four times, five times, or more, in order to create adequate current density to reach and stimulate the nerve branch. The resulting nerve signal, however, may exhibit a similar amplification to double, three times, four times, five times, or more, relative to the compound action potential created when each electrode is stimulated at a lower level. The resulting larger signal may exhibit a greater signal-to-noise ratio, or may reduce latency problems that can result when different nerve endings are stimulated. Because the current density stimulates the nerve branch itself, and not multiple endings of the branch, the larger signal is a single propagating signal rather than a compound action potential that is timed up by synchronizing electrode stimulation timing.

Using multiple electrodes and properly timing their stimulations can reduce interference from noise in detected nerve responses. When only one electrode is used to deliver stimulation or only one branch of a nerve is stimulated, the resulting nerve response may be susceptible to noise interference caused by the delivered stimulation or other external interference sources. Whereas a single signal triggered from one individual electrode may have a low signal-to-noise ratio, the ratio can be decreased by each electrode or stimulated nerve branch contributing to the propagating signal. Timed stimulation from the electrodes that produce the strongest nerve responses from multiple branches of the stimulated nerve provides signals having preferable signal-to-noise ratio.

The system shown in FIG. **1** may monitor for sensory nerves and responses only. Using such a system, a surgeon can avoid pure sensory nerves, such as the genitofemoral nerve, as well as mixed nerves that include some sensory nerve fibers. The sensory system may be employed in a surgery in tandem with a second neuromonitoring system that monitors for motor nerves, and the two systems together may provide guidance to a surgeon in avoiding sensory, motor, and mixed nerves. In some implementations, the neuromonitoring system shown in FIG. **1** may incorporate motor monitoring components into the neuromonitor **2** in order to monitor for all three types of nerves without the need for a second neuromonitoring unit. The combined neuromonitoring system, under the control of neuromonitor **2**, delivers stimulation to and detects responses from both motor and sensory nerve tissues with one system, thus providing full monitoring of the nervous anatomy.

While the combination of stimulation delivered from the array **12** and detection of nerve responses at the instrument **4** monitors and detects sensory nerves near the spine, the stimulation from array **12** does not produce a measurable response from motor nerves exiting the spine in the proximity of the distal end **16** of the instrument **4**. In order to monitor for both sensory and motor nerves, the instrument **4** may be configured with multiple electrodes that serve a dual purpose—acting as both a nerve sensor (for sensory nerves) and a nerve stimulator (for motor nerves). Similarly, the sensor array **12** may also serve a dual purpose, having both nerve stimulating electrodes (for sensory nerves) and EMG response sensors (for motor nerves). Examples of motor nerve stimulating and detecting components and approaches are discussed in U.S. Provisional Application Nos. 61/721,482, 61/796,207, and 61/730,202, which are hereby fully incorporated by reference herein.

In addition to the sensors that detect nerve responses from sensory nerves, such as the two branches **10** and **11** of the genitofemoral nerve, the distal end **16** of the instrument **4** may include one or more stimulating electrodes that are controlled by the neuromonitor **2** to emit stimulus signals. These stimulus signals cause motor nerves in the proximity of the distal end **16** to depolarize and trigger a muscle contraction response in peripheral muscles innervated by the motor nerves. The inclusion of stimulating electrodes allows the instrument **4** to stimulate nearby motor nerves while still detecting (in timing offset from the delivered stimulus) the responses of sensory nerves located in the same area. Muscle responses elicited by the stimulation delivered from instrument **4** are detected by electrodes placed on the patient's skin over the muscle groups innervated by the motor nerves or embedded in the muscle tissue. For example, the system may include electrodes **6***a-c*, which may be surface EMG electrodes that pick up electrical muscle activity when one or more of the muscles beneath the skin is stimulated. These muscle responses are passed to the neuromonitor **2** through the connection **22** and are processed by the neuromonitor **2** to determine when a muscle response has been evoked by stimulus delivered by the instrument **4**. Though the electrodes **6***a-c* are shown with a wired connection in FIG. **1**, these electrodes, like the other components in the system, may communicate with the neuromonitor **2** via a wireless communications link.

The neuromonitoring components located on the instrument **4** provide the dual functions of the instrument—to act as both a nerve stimulator and a nerve response sensor. For motor nerve monitoring, the stimulating electrodes on instrument **4** deliver electrical stimulus to the tissue near spinal nerves to trigger neuromuscular responses from motor nerves. Such electrodes include monopolar and bipolar electrodes that are electrified on the instrument **4** and emit electrical signals into surrounding tissue when neuromonitor **2** initiates stimulation. For sensory nerve monitoring, the response sensors on instrument **4** sense body potentials in the tissues surrounding the instrument **4**. When a sensory nerve near the instrument is stimulated, a propagating action potential is detected by the response sensors as a deviation from resting body potential caused by depolarization and repolarization of the nerve. The neuromonitor **2** serves as the controlling logic instrument for both the motor and sensory nerve detection systems. For example, a processor or control circuitry in the neuromonitor **2** is programmed or otherwise configured to execute algorithms and perform one or more of the functions that deliver stimulation, receive signals, process information, or perform communications within the system. In particular, when both response sensors and stimulating electrodes are placed on the instrument **4**, the neuromonitor **2** times delivery of stimulus from the stimulation electrodes and detection of sensory responses at the response sensors such that the two systems do not interfere with each other. Because both the motor nerve stimulators and sensory nerve response sensors are placed near each other at the end of the instrument **4**, the timing and synchronization of neuromonitor **2** reduces cross-talk and interference between the two types of nerve monitoring approaches.

In implementations in which instrument **4** acts as both a nerve stimulator and a nerve response sensor, the system can detect both sensory and motor nerves in the vicinity of the spine. The stimulation and sensing for both motor and sensory nerves performed by the electrodes and sensors on the instrument **4**, the electrode array **12**, and the sensors **6***a-c* are all controlled and synchronized by the neuromonitor **2** to reduce mixing signals or creating false electrical responses from the two stimulation and sensing components. For example, the stimulation delivered from the array **12** and the corresponding nerve response detected by a response sensor on the instrument **4** can be timed to sync with the motor nerve stimulus delivered from the instrument **4** and the corresponding muscle responses at the sensors **6***a-c*. In this way, motor nerve stimulation delivered from the instrument **4** does not interfere with sensory nerve response detection at the instrument **4**, and stimulation from the array **12** does not cause false positive responses to be detected at the sensors **6***a-c*. Synchronization of the stimulation and response detection for both motor and sensory nerves is described in more detail below with respect to FIG. **11**.

Sensory probes, such as instrument **4** and/or one or more peripheral electrodes (e.g., one or more of electrodes **6***a-c* in FIG. **1**, can also be used to create a detailed map representative of the nerve anatomy around a surgical site prior to beginning a surgical procedure. As described above, in implementations in which the instrument combines a motor nerve stimulator and a sensory nerve response sensor, the system obtains electrical signals that can be used to determine the location of nerves and create maps of both sensory and motor nerve locations. When multiple probes are provided, or instrument **4** includes multiple branches that analyze adjacent tissue locations, the neuromonitor **2** can execute a combined sensory and motor nerve detection algorithm to create the nerve map with both types of nerves. The surgeon can then plan a surgical approach and procedure that takes into account both types of nerves using a single map. Detecting nerve locations and mapping sensory and motor nerves is described in more detail below with respect to FIGS. **12-14**.

A sensory nerve neuromonitoring system, optionally combined with the motor neuromonitoring functionality, provides for mapping and monitoring the nervous anatomy. To detect sensory, motor, and mixed nerves with a neuromonitoring system, sensory and motor stimulating and detecting components can be incorporated into the neuromonitoring system. Such a combined nerve monitoring system is illustrated by neuromonitoring system **300** in FIG. **2**. The system **300** includes a display **302**, a neuromonitor **304**, a surgical instrument **306**, a sensory nerve stimulator **308**, and a muscle response detector **310**. The neuromonitor **304** provides processing control and logic that creates an operational interface between the display **302** and the sensing and detection components of the system **300**. The neuromonitor **304** includes a processor or other logic circuitry programmed to control delivery of stimulation to various patient tissues, receive detected responses to delivered stimulations, and process the stimulus and response data to provide information and intraoperative guidance to a surgeon on display **302**. The neuromonitor **304** is equipped to be toggled quickly between a first state in which it initiates tissue stimulation at stimulating electrodes connected to the neuromonitor and a second state in which it receives detected electrical signals from sensors placed within or on tissue. The stimulations delivered can be adjusted by the neuromonitor **304**, and may include stimulations at varied current amplitudes, frequencies, voltages, or other variable characteristics. For example, stimulations may be delivered at current amplitudes between about 1 mA and about 100 mA, voltages between about 1V and about 100V, and frequencies between about 1 msec and about 1 sec. The neuromonitor **304** may include, for example, a Cadwell Cascade® neuromonitoring unit, or any other suitable neuromonitoring equipment made by Cadwell Laboratories, Inc.

Components of the system **300** that are controlled by the neuromonitor **304** and provide for neuromonitoring of both motor and sensory nerves are provided on a surgical instrument **306**. The surgical instrument **306** is an instrument configured to be positioned near a patient's nervous tissue for nerve monitoring, in some implementations near a patient's spinal anatomy. The surgical instrument **306** may be, for example, a monopolar probe, a tissue dilator (which may be tubular or non-tubular), a tissue retractor, working cannula, a scalpel, a tool for implant placement, a pedicle screw, a guide wire, a sequential access surgical system including multiple instruments, or any other surgical instrument that may be used in surgery. For motor nerve monitoring, surgical instrument **306** includes one or more stimulation electrodes **312** for delivering stimulus signals to tissue surrounding the surgical instrument **306**. For sensory nerve monitoring, surgical instrument **306** includes one or more nerve response sensors **314** that detect changes in potential in tissue surrounding the surgical instrument **306**, for example when a nearby sensory nerve is stimulated and depolarizes as an action potential propagates through the nerve.

The motor nerve monitoring components (e.g., stimulating electrode **312**) of surgical instrument **306** elicit muscle responses detected by peripheral components (e.g., muscle response detector **310**) of the system **300** at muscles stimulated by delivered stimulations. The muscle response detector **310** includes one or more muscle response sensors **318** for detecting muscle activity triggered by motor nerves stimulated by the electrodes **312**. Muscle response sensors **318** may include, for example, skin electrodes, needle electrodes, electromyography sensors (which may include skin or needle electrodes), piezoelectric sensors, other mechanical sensors, or any other suitable sensors for detecting muscle activity.

The sensory nerve monitoring components (e.g., response sensors **314**) of surgical instrument **306** detect the sensory nerve responses elicited by stimulations delivered by peripheral components (e.g., sensory nerve stimulator **308**) at innervated sensory tissues. The sensory nerve stimulator **308** includes one or more stimulating electrodes **316** for delivering stimulus to sensory tissues, such as dermatomes innervated by sensory nerves, in the vicinity of surgical instrument **306**. The stimulating electrodes may include, for example, skin electrodes, needle electrodes, monopolar or bipolar probes, or any other suitable electrodes for delivering stimulus to sensory tissues.

The coordination of the stimulation components and response detection components of system **300** for both motor and nerve monitoring is performed by the neuromonitor **304**. The neuromonitor **304** is programmed to toggle between stimulation and sensing. Processors or other control circuitry of neuromonitor **304** execute algorithms that synchronize the stimulations delivered by electrodes **312**, elicited muscle responses detected by muscle response sensors **318**, stimulations delivered by electrodes **316**, and elicited sensory nerve responses detected by response sensors **314**. The processing components of neuromonitor **304** then process the sensory and motor nerve data received from surgical instrument **306**, sensory nerve stimulator **308**, and muscle response detector **310**, and provides guidance or warnings to the surgeon regarding both sensory and motor nerves in the vicinity of surgical instrument **306** via display **302**. Each of the components of system **300** may be implemented using any suitable combination of hardware circuitry, firmware, and software using computing devices that include processing circuitry, non-transitory computer memory (including volatile and non-volatile units) for storing software programs and/or data (including databases of neuromonitoring sessions data), communication circuitry, user interface (including user input/output controls, and graphical user interfaces, where suitable). The components of system **300** may be connected by cable which carries digitized signals from one component to another, or by wireless communications using serialized or parallel message packets. In some implementations, some of the components of system **300** may be located remotely from other components of the system.

During surgical procedures, such as spinal surgeries, in tissues having motor, sensory, and mixed nerves, sensory and motor monitoring provides for mapping and monitoring full nerve anatomy, rather than just one or two of these three types of nerves. An illustrative combination of sensory and motor nerves that may be in the proximity of a surgical instrument, such as the instrument **4**, during a spinal approach is shown in FIG. **3**. It is understood that due to the complexity of the human anatomy, FIG. **3** illustrates only a few of the nerves that may be monitored, but other nerves would likely be present and can be monitored and detected by similar neuromonitoring principles and technologies. As illustrated, a series of nerves exit the patient's spine **28** through nerve roots on the lateral sides of the spine. These nerves include the genitofemoral nerve, which includes a main branch **24** that exits the spinal cord, with nerve roots **30** and **32** at the level of the L-1 and L-2 lumbar vertebrae. The main branch **24** then splits at a junction **34** into the femoral branch **10** and the genital branch **11** of the nerve. The femoral branch **10** runs down from the junction **34** to a nerve ending **26** that innervates a skin dermatome in the upper part of the femoral triangle on the patient's inner thigh. The genital branch **11** turns medially from the junction **34** and runs to a nerve ending **27** that innervates the cremaster muscle and scrotal skin in males and the mons pubis and labia majora in females. Using the generally known structure and anatomy of the main branch **24** and two forked branches **10** and **11** of the femoral nerve as well as the general position of the nerve endings **26** and **27**, stimulating electrodes, such as the array **12** shown in FIG. **1**, are placed on the skin in the general area of the nerve endings **26** and **27** to stimulate and monitor the proximity of an instrument approaching any of the branches **10**, **11** or **24** during a surgical procedure.

The systems and methods described herein analyze the location and condition of the nerves shown in FIG. **3** before, during, and after surgical procedures. Probes are used before a surgery to investigate the patient anatomy and create a pre-surgical map of the nerves shown in the figure, for example the genitofemoral nerve or other nerves located in or near the psoas major muscle **13**. The map may then be used to pre-plan a surgical approach or guide a surgeon during surgery to reduce the risk of injuring those nerves. During the surgery, stationary probes are positioned near the mapped location of the nerves to monitor the nerve for potential danger or intraoperative damage. All tools used during the surgery may also be electrified to guard against damaging the nerves during approach or intraoperative handling. Following the surgery, probes or other tools are used to assess the post-surgical health of the nerves and check for any complications from the surgery that may cause pain or partial paralysis following the surgery.

FIG. **4** illustrates a process for detecting or monitoring the genitofemoral nerve, or another sensory nerve, during a lateral approach to the spine or a surgical procedure performed at the spine. The detection and monitoring is illustrated by a stimulus profile **40** and nerve response signal **50**. The stimulus profile **40** shows three stimulation pulses **41**, **42** and **43** delivered to a skin dermatome by one or more stimulating electrodes, for example by one or more of the electrodes **14** in the array **12** shown in FIG. **1**. Each of the stimulation pulses **41**, **42** and **43** triggers a sensory response from a sensory nerve that innervates the dermatome to which the stimulations are delivered. As a result, each stimulation pulse **41**, **42** and **43** produces a corresponding nerve response **51**, **52**, and **53** in the nerve response signal **50** detected near the sensory nerve, for example by electrodes on the distal end **16** of the instrument **4** shown in FIG. **1**. The sensed nerve responses **51**, **52**, and **53** are the result of the sensory nerve depolarizing as the sensory nerve action potential propagates from the point of stimulation towards the brain.

Because the stimulation is delivered at the skin dermatome, and the nerve response is measured upstream, for example near the nerve root, there is a latency associated with each of the nerve responses **51**, **52** and **53** relative to their corresponding stimulation pulse **41**, **42** and **43**. For example, the first pulse **41** is delivered at time s_1, and the nerve response in the corresponding sensory nerve begins at time r_1, creating a latency **44** between the stimulation pulse **41** and the sensed response **51**. Likewise, the second stimulation pulse **42** is delivered at time s_2, and the corresponding nerve response **52** is detected at time r_2, creating a latency **45** after the delivery pulse. Finally, the third pair of stimulation pulse **43** and nerve response **53** has a latency **46** that is substantially equal to both latency **44** and latency **45**.

While the nerve responses **51-53** shown in response signal **50** are large, there may be smaller, insignificant responses or noise signals within the response signal **50** that are not true nerve responses caused by the stimulation pulses **41-43**. In order to differentiate noise and insignificant responses from actual triggered nerve responses, an upper threshold **54** and lower threshold **55** may be applied to the response signal **50**, in addition to one or more of any number of known filtering techniques. Only nerve response signals that exceed one or both of these thresholds **54** and **55** are considered true nerve responses. For example, response signal **50** includes a noise portion **56**. The noise portion **56** may be caused by external stimulation, random nerve activity, electrical interference, or any other source of noise and should not be considered a true nerve response. By applying the thresholds **54** and **55**, the noise signal **56** is filtered out, and only the true nerve responses **51**, **52** and **53** are used to assess the nerve characteristics during the spinal surgery.

The stimulus profile **40** and the nerve response signal **50** show three similar stimulation pulses **41**, **42** and **43** producing three similar nerve responses **51**, **52** and **53** having generally similar amplitudes and latencies. The reproducibility of these nerve responses is useful in monitoring the sensory nerve during a surgical procedure. For example, the probe used to deliver the stimulation pulses **41**, **42** and **43** may be left stationary in the vicinity of the monitored nerve while other surgical components are advanced toward or past the nerve to the spine. The neuromonitoring system can deliver subsequent stimulation pulses similar to the three stimulation pulses shown in the stimulus profile **40**, and the amplitude and latency of subsequent nerve responses can be monitored to detect changes in the nerve response signal that may indicate problems or potential damage to the monitored sensory nerve. For example, if the probe is not moved and delivers a fourth stimulation signal, a resultant nerve response having an amplitude that is noticeably smaller than the three responses **51**, **52** and **53** could signal an impingement or other problem. In particular, if that response does not exceed one of the thresholds **54** and **55**, it could indicate that there has been damage to the monitored nerve. In addition, an increase or decrease in the latency of subsequent nerve response signals may indicate that the monitored nerve has been either damaged or is being compressed by the surgical procedure.

FIG. **5** shows a stimulus profile **60** and a nerve response signal **70** for monitoring a sensory nerve with a stationary probe while a surgical procedure is carried out using other surgical instruments. The stimulus profile **60** includes three similar or identical stimulation pulses **61**, **62** and **63** delivered to a dermatome, for example using the array **12** shown in FIG. **1**. The response signal **70** shows three nerve responses **71**, **72** and **73**, corresponding to respective stimulation signals in the sequence **60**. As shown in the response signal **70**, the first two responses **71** and **72** are similar to the responses **51**, **52** and **53** shown in FIG. **4**. These responses indicate that the monitored sensory nerve is intact and not impinged upon during the surgical procedure. The third response signal **73** caused by the stimulation pulse **63**, however, is noticeably smaller than each of the two nerve responses **71** and **72**. The response **73** does not exceed either of the two thresholds **74** and **75**, which are exceeded by both the first and second response signals **71** and **72**. If the probe delivering the stimulus profile **60** is not moved between the stimulation pulse **62** and stimulation pulse **63**, the changed amplitude of the nerve response **73** may be an indication that the monitored nerve has been contacted or damaged in some way. If this is the case during surgery, a warning or other indication is displayed to the surgeon, for example on the display **8** shown in FIG. **1**, communicating that there may be a problem with the monitored nerve, and further evaluation should occur before instruments are advanced any further into the body or spine.

In addition to the change in nerve response amplitude shown in FIG. **5**, a change in response latency may indicate a potential problem with a nerve during surgery. The stimulus profile **80** and nerve response signal **90** shown in FIG. **6** depict such a latency change. Like the stimulation and nerve response sequence shown in FIG. **5**, the first two stimulation pulses **81** and **82** in FIG. **6** elicit two nerve responses **91** and **92** having similar amplitude and latencies **84** and **85**. The third stimulation pulse **83**, however, elicits a nerve response **93** that has a longer latency **86** than the previous responses **91** and **92**. Although the response **93** still exceeds both thresholds **94** and **95**, as responses **91** and **92** do, the increased latency **86** may be an indication that there is an injury or potential problem with the monitored sensory nerve. For example, if a surgical tool is pressed against a monitored nerve and compresses a portion of the nerve, the time required for a nerve signal to travel from the stimulated dermatome to the monitored portion of the nerve may be increased by the compressed portion. As with the decreased response amplitude detected in FIG. **5**, an indication or a warning may be displayed to the surgeon, for example on the display **8** shown in FIG. **1**, that latency has increased and there may be a potential injury or danger to a monitored sensory nerve.

In addition to continuously or intermittently monitoring a sensory nerve from a stationary probe that is known to be near that nerve, the neuromonitors described herein also determine the proximity of a surgical tool to a sensory nerve at an unknown location during lateral approach and access to the spine. An example of stimulation and nerve responses used to determine the proximity of such a nerve are shown in the stimulus profile **100** and nerve response signal **110** in FIG. **7**. The stimulus profile **100** includes three stimulation pulses **101**, **102**, and **103** shown increasing in intensity, and three corresponding nerve responses **111**, **112**, and **113** elicited by the three stimulations. The change in magnitude of the stimulation from pulse **101** to pulses **102** and **103** may be controlled by, for example, changing a current level, a pulse width, or any other suitable characteristic of the stimulation pulse that increases its intensity. The nerve response signal **110** illustrates the increased amplitude of each subsequent response elicited by the stimulus profile **100**. In particular, the first response **111** is a small response that does not approach either of the thresholds **114** or **115**. The second response **112** has a greater amplitude and approaches the thresholds, but still does not exceed either threshold level. For the highest intensity stimulation pulse **103**, the corresponding nerve response **113** exceeds both thresholds **114** and **115** and indicates that the intensity of the stimulation pulse **103** delivered to the innervated dermatome is sufficient to elicit a nerve response in the monitored sensory nerve. This indication may be used to determine, for example, a threshold stimulus intensity required to stimulate the nerve. If the determined threshold intensity, for example the intensity of pulse **103**, is below a safe level, an indication may be provided to a surgeon that the tool sensing the nerve responses **110** is approaching too near to the nerve.

Additional neuromonitoring may be implemented to determine a threshold stimulation required to elicit a sensory nerve response to a desired resolution. For example, once stimulation pulse **103** is determined to elicit a nerve response **113** that exceeds the thresholds **114** and **115**, further stimulation and response testing may be used to determine a narrower threshold window between the intensities of pulses **102** and **103** that contains the minimum required intensity to elicit a substantial nerve response. The additional stimulation and sensing techniques may include providing additional stimulation at intensities between the pulses **102** and **103**, for example using the stimulation techniques discussed with respect to motor nerve monitoring in U.S. Provisional Application Nos. 61/721,482, 61/796,207, and 61/730,202, which are hereby fully incorporated by reference herein.

The approaches shown in FIGS. **4-7** illustrate monitoring techniques for a sensory nerve that can be detected by delivering stimulations to the dermatome near the precise location of a nerve ending, for example the end of the femoral or genital branch of the genitofemoral nerve. In cases where an electrode is used that is not directly on the dermatome innervated by the nerve, the responses sensed by a surgical tool may be minimal, even if the surgical tool is in the vicinity of the nerve. This could result in dangerous situations in which the tool is near or contacting the nerve, but no warning is generated because minor or no nerve responses are detected. Calibration and testing before neuromonitoring can be performed to determine one or more optimal electrodes, for example electrodes in an array such as array **12**, to be used to stimulate the dermatome and elicit detectable nerve responses.

FIG. **8** shows a stimulus profile **120** and a nerve response signal **130** that are delivered and elicited from sensor array **136** during calibration and stimulation configuration. The three stimulation pulses **121**, **122**, and **123** in stimulus profile **120** are delivered from a single stimulation electrode **137** in the array **136**. In response to each of the pulses, nerve responses **131**, **132**, and **133** are detected at a sensor electrode on an instrument used in a lateral spinal approach surgery. For the calibration test, the instrument and response sensor electrode are positioned near the stimulated sensory nerve, but each of the three nerve responses **131**, **132**, and **133** does not exceed either of the thresholds **134** or **135**. The small nerve responses, despite the proximity of the sensor to the nerve, may be a result of the electrode **137** not being positioned on the skin directly over the dermatome innervated by the monitored nerve, or may be a small response because the electrode **137** stimulates only one branch of the nerve ending. Other combinations of the electrodes in array **136**, for example delivery of stimulus from electrodes **138** or **139**, or a combination of those electrodes, may be more preferable for delivering stimulus and may elicit greater responses from the nerve, for example by stimulating additional dermatomes or additional nerve endings on a single dermatome. For example, delivery of a stimulus from either electrode **138** or **139** may elicit the nerve responses **124**, **125**, and **126** using the same stimulation pulses **121**, **122**, and **123**. Because each of these nerve responses **124**, **125**, and **126** are greater in magnitude, and each exceeds thresholds **134** and **135**, delivery of stimulus from these alternative electrodes improves the response detectability and would be preferable. In the calibration process, all of the electrodes in the array **136** may be tested, and those electrodes that elicit the greatest nerve responses, or a combination of those electrodes, may be used for delivery of the stimulus during active neuromonitoring.

In addition to the amplitude of nerve responses elicited by stimulation delivered from different electrodes in an array, each nerve response may have a different latency that can compromise the detectability of active responses from the sensory nerve. The differences in latency may result from the electrodes being positioned different distances from the triggered nerve ending, or positioned near different nerve endings with slightly different response latencies. An electrode that is directly on top of a nerve ending may elicit a nerve response that propagates quickly, while an electrode positioned farther away from the nerve ending may elicit a response that takes longer to propagate to the portion of the nerve monitored by a sensory probe. If the nerve responses are detected at separate times, there may not be one response large enough to trigger a threshold, though all three response are actual nerve responses to the stimulation. During the calibration period, this difference in time latencies can be accommodated both by selecting particular electrodes used to deliver the stimulation and by synchronizing the timing of the stimulations delivered from each electrode. In particular, the stimulation pulses may be synchronized such that the responses elicited by each reaches the response sensor at generally the same time, creating a compound action potential that produces a single large detected nerve response from the sensory nerve.

FIGS. **9** and **10** depict a process for syncing stimulation signals delivered from three different electrodes, for example during calibration and configuration of a sensor array, to elicit a detectable compound action potential from a sensory nerve. The data from this process can also be used to triangulate and detect locations of nerves near these different electrodes. The position of three electrodes **181**, **182**, and **183** in a stimulation array **180** is shown on the right, and stimulus profiles **140**, **150**, and **160** corresponding to electrodes **181**, **182**, and **183**, respectively, are shown on the left. Nerve response signal **170** depicts the electrical nerve activity detected by a sensor probe near the sensory nerve during delivery of the stimulations. Each of the stimulus profiles **140**, **150**, and **160** includes three stimulation pulses delivered from the electrodes **181**, **182**, and **183** simultaneously. In particular, three stimulation pulses **141**, **151**, and **161** are delivered from electrodes **181**, **182**, and **183**, respectively, at time point A_1. The nerve response signal **170** shows three individual detected nerve responses **171***a*, **171***b*, and **171***c* corresponding to each of the stimulation pulses **141**, **151**, and **161**, respectively. No one nerve response exceeds one of the thresholds **174** and **175**, and thus simultaneous stimulation from electrodes **181**, **182**, and **183** does not produce a reliably detectable response from the monitored nerve.

The spreading of the nerve responses **171***a*, **171***b*, and **171***c* results from differences in latencies, or the time it takes a triggered nerve signal to travel from the stimulated dermatome to the area of the nerve monitored by the sensing probe for each electrode stimulation. The first nerve response **171***a*, corresponding to the stimulation pulse **141** from electrode **181**, is received at time B_1, and the latency for this response is L_1, which is the lag from the stimulation time A_1 to the sensed response time B_1. The second nerve response **171***b*, corresponding to the stimulation pulse **151** from electrode **182**, is received at time C_1, which is later than B_1 and lags the stimulation time A_1 by a longer latency L_2. Finally, the third nerve response **171***c*, corresponding to the stimulation pulse **161** from electrode **183**, is received at time D_1, later than both B_1 and C_1, and lags behind the stimulation time A_1 by a longer latency L_3. For subsequent stimulations from the electrodes **181**, **182**, and **183** in array **180**, both the latencies and amplitudes of the three detected nerve responses remain generally constant, as the sensing probe is not moved nearer to or farther from the monitored nerve. Thus, the nerve responses **172***a*, **172***b*, and **172***c*, corresponding to stimulation pulses **142**, **152**, and **162**, and the nerve responses **173***a*, **173***b*, and **173***c*, corresponding to stimulation pulses **143**, **153**, and **163**, exhibit latencies similar to nerve responses **171***a*, **171***b*, and **171***c*.

The nerve responses elicited by each individual electrode are processed by a neuromonitor to determine the amplitudes and latencies of the responses. The neuromonitor uses the determined amplitudes and latencies to time stimulation signals to elicit a larger compound action potential from a nerve and create a more easily detected signal having a greater signal-to-noise ratio. For example, in a calibration phase, each electrode in array **180** delivers sequential stimulation pulses one at a time, and the nerve responses detected for each electrode are analyzed to determine an optimal combination of electrodes exhibiting desired response amplitudes and latencies. A stimulus profile is then generated by a neuromonitor processor or other circuitry and is used to control the selected electrodes to deliver stimulations at different times, as shown in FIG. **10**.

The timing of the generated stimulus profile can be programmed so as to elicit a compound action potential from the sensory nerve. Using test stimulations and responses, the program accounts for differing amplitudes and latencies of the signals obtained from the electrodes shown in FIG. **9**, which may be placed at different distances from the nerve, near different nerve branches, or on different dermatomes. The stimulation controlled by the neuromonitor and the generated program it executes is applied to those locations in a synchronized fashion, so that the responses elicited from those different stimulations are also synchronized, thereby creating a large aggregate signal propagating through the sensory nerve. For example, the neuromonitor (e.g., neuromonitor **2** in FIG. **1**) is programmed to process the test stimulation and test response data and select the electrodes that elicit larger responses, as those responses also produce a larger signal-to-noise ratio. The neuromonitor then uses the latencies for each of the selected electrodes to program a delay in stimulation at electrodes that elicit faster responses, so that the aggregate responses arrive at or near the same time in the area of the nerve monitored by the response sensor.

FIG. **10** depicts three stimulus profiles **190**, **200**, and **210** for the electrodes **181**, **182**, and **183**, respectively, which are not delivered simultaneously but rather are offset and synchronized based on the three latencies L_1, L_2, and L_3 determined from the stimulations and responses shown in FIG. **9**. The timing of stimulus profiles **190**, **200**, and **210** is calculated by the neuromonitor in order to elicit individual responses that reach the sensor probe at substantially the same time, creating the compound action potential that creates a single detectable response each time the three electrodes deliver stimulation. The resulting nerve responses **221**, **222**, and **223** in the nerve response signal **220** do not exhibit the spread of three distinguishable responses shown in FIG. **9**, but rather each one is a single peak that exceeds the thresholds **224** and **225**. The thresholds **224** and **225** are applied to the response signal **220** to differentiate small deviations from noise or interference from true nerve response signals. The large peaks in responses **221**, **222**, and **223** provide easily detectable signals that allow these thresholds to be applied to cut out noise while reducing the risk of missing actual nerve response signals.

The stimulation pulses **191**, **201**, and **211** delivered by the electrodes **181**, **182**, and **183**, respectively, are timed by the neuromonitor such that their latencies are accounted for, and each pulse elicits a nerve response that reaches the probe at response time D_2, as shown for the nerve response **221**. To elicit this response, the electrode having the longest latency in FIG. **9**—latency L_3 for electrode **183**—is pre-programmed to deliver a stimulation pulse **211** first, at time A_2. The electrode with the second-longest latency in FIG. **9**—latency L_2 for electrode **182**—is pre-programmed to delay stimulation for the difference X_1 of latencies L_3 and L_2 and then deliver a stimulation pulse **201** at time B_2. Finally, the electrode with the shortest of the three latencies in FIG. **9**—latency L_1 for electrode **181**—is pre-programmed to delay stimulation for the additional difference X_2 of latencies L_2 and L_1 and deliver a stimulation pulse **191** at time C_2. After each of the pulses are delivered, the nerve signals aggregate, and the compound action potential creates response **221** at time D_2, at the synchronized end of each of the three latencies. Because the three latencies are generally constant as long as the nerve is not damaged or compressed, further stimulation with the same timing produces repeatable responses. The subsequent pulses **192**, **202**, and **212** produce another compound action potential measured by the probe at response **222**, similar to response **221**. Finally, a third timed sequence of stimulation pulses **193**, **203**, and **213** elicits a third compound action potential and detected response **223**.

Synchronizing stimulation pulses delivered to a dermatome and sensory nerve can elicit a more distinguishable response signal from the nerve and thereby facilitate detection of nerve action potentials in the signal. In systems where both motor and sensory nerves are monitored simultaneously, and particularly when a surgical instrument incorporates both a sensory nerve response sensor and a motor nerve stimulating electrode, further synchronization between the motor and sensory monitoring components can also improve the clarity of response signals. In particular, synchronization among the components can be used to reduce cross talk in the system and reduce the risk of contaminating received response signals for one component with delivered stimulus signals from the other component.

FIG. **11** shows a synchronized stimulating and sensing sequence for a neuromonitoring system that includes both sensory and motor nerve monitoring components on a single instrument, for example instrument **4** shown in FIG. **1**. In the sequence shown, the instrument is placed near both a sensory nerve and a motor nerve, and both nerves are monitored by the system. The sequence includes a sensory nerve response signal **230** detected by a response sensor on the instrument, as well as a motor nerve stimulus profile **240** delivered by a stimulating electrode on the probe. The sensory response signal **230** detected at the instrument is elicited by sensory stimulus profile **250**, which is delivered by surface electrodes to a dermatome innervated by the monitored sensory nerve. The motor stimulus profile **240** emitted by the instrument elicits a motor nerve response signal **260**, detected by EMG electrodes at muscles innervated by the monitored motor nerve.

A neuromonitor, such as the neuromonitor **2** in FIG. **1**, executes an algorithm that causes the stimulations in stimulus profile **240** to be delivered to the surgical instrument and the stimulations in stimulus profile **250** to be delivered to the dermatome surface electrodes at set times. In response to each of the stimulations in the profiles **240** and **250**, the neuromonitor receives nerve response signals **230** and **260** elicited by profiles **240** and **250**, respectively. The neuromonitor does not control the delay between a stimulation and a detected response for a given sensory or motor nerve, as that delay is the result of response latency of the nerve itself, but is pre-configured to time the stimulations that are delivered such that the stimulations and the delayed elicited responses do not mix. It is preferable to properly time the stimulations delivered to both the sensory and motor nerves such that the nerve response signal **230** and stimulus profile **240**, which are received and delivered from sensors and electrodes near each other on the surgical instrument do not interfere with each other. Using pre-defined values for latencies between stimulation and response detection for both the sensory and motor nerves, the neuromonitor creates stimulus profiles that reduces overlap between the electrical signals, as shown in the stimulations and responses in FIG. **11**.

The monitoring process in FIG. **11** begins with delivery of a first stimulation pulse **251** at time T_1 to a peripheral sensory tissue innervated by the monitored sensory nerve. The pulse **251** elicits a response from the sensory nerve that is detected at the instrument as response **231**. Due to latency in the signal propagation, the response **231** is detected at a time T_2 that lags the stimulation time T_1 by the duration of the latency X_1. If the latency is X_1 for the monitored sensory nerve, the neuromonitor that synchronizes the stimulations can wait for a pre-defined period that corresponds to that latency to allow time for the nerve response to be received by the response sensor on the surgical instrument before triggering the motor nerve stimulation pulse **241** at time T_3. This delay reduces the risk of producing a false negative detection in the response signal **230** caused by the response sensor disposed on the instrument near the stimulating electrode detecting the stimulation pulse **241**. As shown in the response signal **230**, interference **232** is detected at the response sensor when the stimulation pulse **241** is delivered. The interference **232** is picked up by the sensor because both the sensor and the stimulating electrode are on the distal end of the surgical instrument, and thus any stimulation delivered by the instrument is also detected by the instrument.

Using the latency X_1 and the known or estimated time during which nerve response **231** is detected, the neuromonitor delays the stimulation pulse **241** an additional lag time X_2 beyond the latency X_1 after delivery of stimulation pulse **251**. The time X_2 preferably includes a buffer beyond the response detection time in case detected nerve responses, such as response **231**, are longer than expected. Once the stimulation pulse **241** is delivered at time T_3, the neuromonitor then ignores any response seen in the response signal **230** for a short time period in order to filter out noise from detecting the stimulation, for example at interference **232**.

From the stimulation pulse **241**, a motor nerve is stimulated, and a subsequent muscle response **261** is detected in the muscle innervated by the nerve at time T_4. As with the nerve response **231**, the muscle response exhibits a latency X_3 as the stimulated signal propagates from the nerve root to the muscle. Following the detected muscle response **261**, the neuromonitor begins the timed monitoring protocol again, with a stimulation pulse **252** delivered to the sensory tissue at time T_5. As the process repeats, the timing of the stimulations delivered by the neuromonitor in subsequent sequences produces detectable nerve and muscle responses and reduces cross talk between the sensory and motor nerve monitoring components. The subsequent stimulation pulses **242** and **243** delivered from the surgical instrument are timed with a long enough delay from respective stimulation pulses **252** and **253** delivered to the sensory tissue that the elicited nerve responses **233** and **235** are detectable and not affected by interferences **234** and **236** corresponding to the pulses **242** and **243**.

The combination of sensory and motor nerve monitoring, and the synchronized timing between stimulations and response detections for the two types of nerves, can be used pre-operatively, intraoperatively, and post-operatively to assess nerve anatomy, location, and health. Changes in the nerve responses, such as changes in response amplitude or response latency, are discussed above as indicators of intra-operative or post-operative deviations from normal nerve functioning that signal danger or injury to the nerve. For pre-operative assessment, a sensory nerve monitoring system, or a combined sensory and motor nerve neuromonitoring system, is used to explore the nerve anatomy and create a map of the anatomy that is used to plan surgery or to guide the surgeon during a procedure.

FIGS. **12-14** illustrate a neuromonitoring system used for a pre-operative assessment to locate and map sensory and motor nerve anatomy. The neuromonitoring system includes a probe **400** for assessing and mapping nerve anatomy, neuromonitor **404** coupled to the probe **400**, a stimulating sensor array **408**, and muscle response sensors **412***a-c*, similar to the systems described above. In contrast to a surgical tool or probe that has one distal point for detecting nerves, the probe **400** has three different probe ends **402***a*, **402***b*, and **402***c*. Each of the probe ends **402***a*, **402***b*, and **402***c* includes one or more stimulating electrodes and one or more nerve response sensors, which allows the probe **400** to detect electrical signals from both sensory and motor nerves, for example sensory nerve **500** and motor nerve **502** shown in FIG. **12**. Those signals are sent to the neuromonitor, and a processor calculates nerve distances and locations with respect to the stimulation electrodes. When multiple distances and locations are determined by the processor in neuromonitor **404**, the locations are graphed in a three-dimensional space to create a "map" of the nerve, which my be provided to a surgeon on display **406**.

During pre-surgical assessment and mapping implementations, the probe **400** is advanced towards the spine until nerves are detected. As explained further below, the neuromonitor **404**, determines distance between the probe and the nerves by processing stimulations delivered and responses detected from each end of the probe ends **402***a*, **402***b*, and **402***c*, and maps the nerve. To obtain the data used by neuromonitor **404** to map the anatomy, the probe **400** is moved to multiple positions within the tissue, and multiple triangulations are performed to determine multiple locations of the nerve and create a representative map of the nerve anatomy.

To locate a motor nerve, the neuromonitor **404** controls delivery of stimulation pulses from the probe ends **402***a-c* to stimulate motor nerves in the vicinity of probe **400**. The stimulations cause muscle responses, and the neuromonitor **404** receives muscle response data after each stimulation from muscle response sensors **412***a-c*. The sensors **412***a-c* are positioned on muscles that are innervated by different motor nerves, and the processing circuitry of neuromonitor **404** correlates the sensor at which a response is detected to a particular motor nerve known to innervate the muscle monitored by that sensor. For example, the neuromonitor **404** may retrieve stored data in memory or may receive input from a surgeon identifying the muscle each sensor is monitoring. The processing circuitry associates each sensor with a given spinal nerve based on the identified muscle. When a nerve is detected and a location on the nerve is determined by the processor of neuromonitor **404**, the neuromonitor stores the determined location with others previously determined for the same nerve. After multiple locations on a particular nerve are found, the processor creates a map by drawing connections between the determined locations for that nerve.

The neuromonitor **404** processes the characteristics—i.e., the current, frequency, or voltage—of the delivered stimulations and the characteristics of the detected muscle responses to determine the proximity of each probe end **402***a-c* to the motor nerve, for example nerve **502** in FIG. **12**. The neuromonitor **404** may process the stimulations and responses to calculate a distance and/or a direction from each probe end **402***a-c* to the nerve. In some implementations, a processor in neuromonitor **404** is programmed with an algorithm that uses the stimulating charge and applies Coulomb's law to determine the distance between one of the probe ends **402***a-c* and the nerve. Coulomb's law can be expressed as $Q=k(Q_0/r^2)$, where Q is the stimulating charge, k is a function of the nerve, Q_0 is the minimum charge needed to stimulate the nerve, and r is the distance between the probe end and the nerve. The programmed processor retrieves known values for k and Q_0 for the particular nerve being mapped, processes the stimulating charge that stimulated the nerve, and calculates r from this equation. In other implementations, other algorithms or equations are applied by the processing circuitry of the neuromonitor **404** to determine the distances from probe ends to the nerve, and such equations may use the stimulating current, as well as one or more other characteristics of the stimulation or the nerve response, to find the distances.

At each position of the probe **400**, three distances and directions to the nerve, corresponding to each of the probe ends **402***a-c*, are processed to triangulate the location of the nerve relative to the probe **400**. The determined location of the nerve relative to the probe **400** is stored in memory in the neuromonitor **404**, along with any other previously-determined locations on the same monitored nerve. The surgeon repositions the probe **400** and retests a different area of the nerve to find other locations on the nerve. At each probe position, the nerve location is determined and stored as another point on the map of the nerve. When a sufficient number of locations have been determined to create a map having an adequate resolution, the processor plots the locations stored in memory in a three-dimensional space and creates map of the nerve's path through the monitored anatomy by connecting the plotted locations.

The sensory nerves are also mapped by the neuromonitor **404** and probe **400**. To locate a sensory nerve, the electrodes **410** in electrode array **408** are placed on the patient near or on a dermatome that is innervated by the nerve to be mapped. The neuromonitor **404** executes a timed protocol for delivering stimulation and controls the electrodes **410** to deliver the stimulation to the dermatome. The delivered stimulation elicits a propagating action potential response from the nerve, for example from sensor nerve **500** in FIG. **12**. This response is detected by response sensors on each of the probe ends **402***a-c* on the probe **400** near the nerve **500**, and the responses are communicated to the neuromonitor **404**. Because the probe ends **402***a-c* are in slightly different positions, they do not detect exactly the same nerve response. The responses detected by each probe end are processed by the neuromonitor to determine the distances from each probe end to the nerve. Similar to the motor nerve triangulation, the probe **400** is moved to different positions in the tissue, and the responses detected at each of the multiple locations are used to locate points along the nerve. The located points are then stored at the neuromonitor **404** and identified with respective locations of the nerve, and the subsequent assessments in different positions are used to create a map of the sensory nerve anatomy.

The responses from sensory nerve **500** obtained at each of probe ends **402***a-c* indicate the distance and direction from each probe end to the nerve. The responses **504**, **506**, and **508** shown in FIG. **14** are three representative responses detected by each of probe ends **402***a*, **402***b*, and **402***c*, respectively, in the positions of the probe ends shown in FIGS. **12-14**. Each of the responses **504**, **506**, and **508** are elicited by stimulation applied by electrode array **408** at or near the peripheral sensory tissue innervated by sensor nerve **500**. Because probe end **402***a* is located nearest the sensory nerve **500**, the propagating action potential shown in response signal **504** detected at probe end **402***a* is the largest of the three responses. The responses **506** and **508** depict slightly smaller action potentials, and are nearly equal as a result of the positioning of the probe ends **402***b* and **402***c* roughly equidistant from the sensory nerve **500**. The orientation of the responses **506** and **508**, however, are opposite, as the response **506** begins with a downward deviation while the response **508** begins with an upward deviation. This difference in orientation indicates a different direction from the probe ends **402***b* and **402***c* to the nerve **500**, as shown in FIG. **14** with the probe ends located both anterior (**402***b*) and posterior (**402***c*) to the nerve **500** when viewed in this lateral direction.

The distances and responses detected in an example sensory nerve mapping process are depicted in the anterior view of the nerves and probe shown in FIG. **13** and the lateral view of the nerves and probe shown in FIG. **14**. The probe **400** is positioned nearer to the sensory nerve **500** than to the motor nerve **502**, which runs anteriorly and medially from the sensory nerve **500**. The probe end **402***a* is positioned nearest the sensory nerve **500**, at a distance d_1, while the probe ends **402***b* and **402***c* are positioned slightly farther from the sensory nerve **500**, at distances d_3 and d_4, respectively. Because they are approaching from the lateral side, all three probe ends are positioned nearer the lateral sensory nerve **500** than the medial motor nerve **502**, as shown with distance d_2 from motor nerve **502** to probe end **402***a*. In this orientation, it may be preferable to map the sensory nerve **500**, then use the map of the sensory nerve **500** to guide positioning the probe **400** around the nerve and closer to motor nerve **502** to obtain a map of that nerve.

From the positioning of the probe in FIGS. **12-14**, the neuromonitor **404** delivers stimulation and processes responses to determine a location on each of the nerves **500** and **502**. The locations may be provided to a surgeon in real time, for example by updating a developing map on the display **406** with the nerve locations as they are determined. The surgeon then moves the probe **404** to obtain more data points and fill out the map of the nerve anatomy. For example, as shown in FIG. **14**, the probe ends **402***a-c* may be moved anteriorly to the positions **402***d-f* and advanced medially to move closer to motor nerve **502** while maneuvering around sensory nerve **500**. This repositioning may be preferable if sensory nerve **500** has already been adequately mapped and the surgeon wishes to obtain more data for motor nerve **502**. Alternatively, the probe ends **402***a-c* can be moved to positions **402***g-i* to obtain more data for sensory nerve **500** and continue mapping the path of that nerve.

The foregoing is merely illustrative of the principles of the disclosure, and the systems, devices, and methods can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation. It is to be understood that the systems, devices, and methods disclosed herein, while shown for use in spinal surgical procedures, may be applied to systems, devices, and methods to be used in other surgical procedures performed in the proximity of neural structures where nerve avoidance, detection, or mapping is desired, including, but not limited to selected brain surgeries, carotid endarterectomy, otolaryngology procedures such as acoustic neuroma resection, parotidectomy, nerve surgery, or any other surgical procedures.

Variations and modifications will occur to those of skill in the art after reviewing this disclosure. The disclosed features may be implemented, in any combination and subcombination (including multiple dependent combinations and subcombinations), with one or more other features described herein. The various features described or illustrated above, including any components thereof, may be combined or integrated in other systems. Moreover, certain features may be omitted or not implemented.

Examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the scope of the information disclosed herein. All references cited herein are incorporated by reference in their entirety and made part of this application.

What is claimed is:

1. A method of neuromonitoring, comprising:

delivering test stimulus signals to different combinations of stimulating electrodes disposed at or near a dermatome or myotome innervated by a first nerve, wherein each of the different combinations of stimulating electrodes have a known configuration;

receiving nerve response signals detected by a response sensor disposed in tissue near the first nerve, wherein each of the nerve response signals corresponds to one of the test stimulus signals delivered to one of the different combinations of stimulating electrodes;

measuring a nerve response time associated with each of the nerve response signals using a calibration sensor;

determining a characteristic of the first nerve based on the nerve response signals and corresponding nerve response times;

determining a distance between the different combinations of stimulating electrodes and the first nerve based on the characteristic and nerve response time of the first nerve; and

using a processor, processing the test stimulus signals and nerve response signals to automatically select an optimum one of the different combinations of stimulating electrodes, wherein processing the test stimulus signals comprises determining a response latency associated with each stimulating electrode of the different combinations of stimulating electrodes;

synchronizing test stimulus signals for the selected combination of stimulating electrodes, wherein synchronizing the stimulus signals comprises delivering or delaying the test stimulus signal depending on the determined response latencies; and

communicating an indication of a location of the nerve to a user, wherein the location is determined using the distance between the different combinations of stimulating electrodes and the first nerve.

2. The method of claim **1**, comprising delivering test stimulus signals individually from each of the different combinations of stimulating electrodes.

3. The method of claim **1**, wherein processing the test stimulus signals comprises determining a response amplitude associated with each stimulating electrode of the different combinations of stimulating electrodes.

4. The method of claim 3, wherein processing the test stimulus signals comprises selecting stimulating electrodes having the largest response amplitudes.

5. The method of claim 1, wherein synchronizing the stimulus signals for the selected combination of stimulating electrodes based on the determined response latencies comprises delivering a test stimulus signal from a first selected stimulating electrode of the selected combination of stimulating electrodes having a longest response latency and delaying test stimulus signals delivered from subsequent selected stimulation electrodes of the selected combination of stimulating electrodes having shorter response latencies.

6. The method of claim 5, wherein the test stimulus signal delivered from each of the subsequent selected stimulation electrodes is delayed by a difference between the longest response latency and a response latency associated with the subsequent selected stimulation electrode.

7. The method of claim 1, comprising determining a proximity of the first nerve to the response sensor using the determined location of the first nerve.

8. The method of claim 1, wherein the calibration sensor is part of the response sensor.

9. The method of claim 6, wherein the nerve response signal from each of the different combinations of stimulating electrodes is received at the same time in the known geometric arrangement in tissue near the first nerve to determine the location of the first nerve.

10. The method of claim 1, wherein the characteristic associated with each of the nerve response signals includes at least one of a response amplitude and a response latency determined based on the nerve response time.

11. The method of claim 4, wherein the selected stimulating electrodes are selected in response to having amplitudes greater than a threshold predetermined by the user.

12. The method of claim 11, wherein the threshold is selected to filter out noise from at least one of the nerve response signals.

13. The method of claim 1, wherein determining the response latency comprises determining the nerve response time of each of the different combinations of stimulating electrodes.

14. A system of neuromonitoring, the system comprising memory coupled to at least one processor configured to:

deliver test stimulus signals to different combinations of stimulating electrodes disposed at or near a dermatome or myotome innervated by a first nerve, wherein each of the different combinations of stimulating electrodes have a known configuration;

processing nerve response signals detected by a response sensor disposed in tissue near the first nerve, wherein each of the nerve response signals corresponds to one of the test stimulus signals delivered to one of the different combinations of stimulating electrodes;

measure a nerve response time associated with each of the nerve response signals using a calibration sensor;

synchronizing test stimulus signals for a selected combination of stimulating electrodes based on the measured nerve response times;

determine a characteristic of the first nerve based on the nerve response signals and corresponding nerve response times;

determine a distance between the different combinations of stimulating electrodes and the first nerve based on the characteristic and nerve response time of the first nerve; and

communicate an indication of a location of the nerve to a user, wherein the location is determined using the distance between the different combinations of stimulating electrodes and the first nerve.

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